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SEDIMENTATION IN SUNWAPTA LAKE, JASPER NATIONAL PARK, ALBERTA

by

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A THESIS

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled SEDIMENTATION IN SUNWAPTA LAKE, JASPER NATIONAL PARK, ALBERTA submitted by PATRICIA MARY WANKIEWICZ in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in GEOGRAPHY.

Dedication

To my Parents

Abstract

Sunwapta Lake is a small proglacial lake adjacent to the retreating Athabasca Glacier (Columbia Icefield, Jasper National Park). Discharge in the Sunwapta River has been monitored since 1948, and work on sedimentation in the lake has been carried out in previous years. During the melt season of 1975, suspended sediment distribution and deposition were studied, based on samples of suspended and dissolved sediment from the inflow stream and the lake, sediment pan samples from the lake bed, discharge measurements from the inflow and outflow streams, temperature records, and core samples taken with a gravity corer. From the data, sediment input, patterns and processes of sediment distribution (by overflow, interflow, and underflow) in the lake and rates of sedimentation were computed. The results and the core samples were compared with results and cores obtained in previous research. Interpretation of changes in Sunwapta Lake sedimentation may be useful in studies of Pleistocene, as well as modern, proglacial lakes.

Acknowledgements

I wish to thank, first of all, my supervisor, Dr. John Shaw, for his help and encouragement over the years. I would also like to acknowledge Dr. Robert Gilbert, whose advice and assistance in the field were invaluable; Dr. Harry McPherson, my temporary supervisor; Pam Osadchuk, my field assistant; Dr. Michael Church, for the use of his equipment; Parks Canada, for allowing me to investigate sedimentation in Sunwapta Lake; John Archer and Don Kvill, for their help in the laboratory; Desmond Wynne, for his time and knowledge with regard to computer programming and preparation of the text and graphs; my sisters, Barbara and Christine, for typing the first drafts; and last, but not least, my family and friends, whose encouragement has been greatly appreciated.

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1. INTRODUCTION

1.1 General

Sedimentation studies have been carried out on several glacial lakes in North America, with variable results (Kindle, 1930; Mathews, 1956, 1964a and 1964b; Gilbert, 1972a and 1972b, 1975a and 1975b; Ashley, 1975; Church and Gilbert, 1975; Gustavson, 1975; Kennedy, 1975). Processes of sediment distribution and rates of sedimentation differ, not only between lakes but within each lake through time and space. Such differences are the result of variations in sediment supply and the characteristics of lake water and inflowing stream water (Johnston, 1922; Kindle, 1930; Mathews, 1956; Gilbert, 1972a and 1972b, 1975a and 1975b; Kennedy, 1975).

Before reviewing literature on sedimentation, some clarification of terms is necessary, particularly as various authors use different terms for the same phenomenon or process. Although 'sedimentation' by definition refers to a complete cycle involving origin, transport, deposition and consolidation of sediment, many writers employ a much narrower definition. Fluvial sedimentation, processes of sediment transport and deposition in streams, is often distinquished from lacustrine sedimentation, processes of sediment transport and deposition in standing water bodies (Kindle, 1930; Mathews, 1956; Fulten and Pullen, 1969). The term 'sediment' refers to the solid material suspended, or

otherwise transported, by water. 'Dissolved sediments' are those substances (such as soluble salts) that combine with a liquid to form a solution. Since this material is not deposited in the same manner as suspended sediment and, in glacial lakes, its effects on density are often masked by large concentrations of suspended sediment, it is frequently disregarded in terms of sedimentation. 'Suspended sediment' refers to those particles whose individual weights are equal to, or less than, their respective immersed weights because of the "... upward momentum or flux of momentum in turbulent eddies in the flow" (Leopold, Wolman, and Miller, 1964). Morisawa (1968) sums up the dynamic forces acting on a small spherical grain in suspension as:

$$6\pi r\mu V + 4/3\pi r^3\rho_2 g = 4/3\pi r^3\rho_1 g \tag{1-1}$$

where $\frac{4}{3}\pi r^3$ is the volume of the sphere; V, the settling velocity; μ, the fluid viscosity; ρ_2, the density of the fluid; g, the acceleration due to gravity; and ρ_1, the density of the grain. By algebraic rearrangement of the known and unknown variables, it is possible to determine the velocity of settling for a small spherical grain:

$$V = \frac{2/9gr^2(\rho_2-\rho_1)}{\mu} \tag{1-2}$$

This is known as Stokes' Law. The actual rate of settling of fine particles is influenced by particle shape, circulation patterns within the lake, wind-generated turbulence, settling distance, vertical temperature differences within

the lake, and variations in suspended sediment concentration with depth.

Density is one of the most important factors affecting sedimentation. Defined as "the mass per unit volume" (Prandtl, 1952), and usually measured as g/cm³, density (ρ) is a component of the weight of a solid or fluid ($w=v_{\rho}g$). An increase in density will increase the weight (w), if the volume (v) and the force of gravity (g) remain constant. Harleman (1961) suggests that density differences between two moving fluid masses, or between a moving and a stationary fluid, result in stratified flow. The denser fluid will sink below the less dense fluid; conversely, a lighter, inflowing fluid will remain above a stationary fluid. Harleman defined stratified flow as "... fluid motions in a gravitational field which are originated or influenced by variations in density within the fluid ..." Similarly, Bell (1942) defined a density current as "... a gravity flow of a liquid or a gas through, under or over a fluid of approximately equal density." In this paper, only stratified flow in a water/sediment complex is considered. Stratified flow is here equated with density currents, or density flow. A particular type of density current, resulting from variations in suspended sediment concentration, is referred to as a "turbidity current" or "turbidity flow".

The vertical position of the current within a standing water body determines the type of density current: overflow,

interflow or underflow. Overflow is the movement of a more or less discrete water/sediment complex over the surface of a water body. Interflow is the movement of a more or less discrete water/sediment complex within a body of water. According to Harleman (1961), an underflow is "... a steady uniform flow of a lower-layer fluid ... along an incline when the driving gravity force per unit area (due to the density difference between the two fluids) is in equilibrium with the shear stress exerted by the fixed boundary and the moving interfacial boundary." In lakes, the fixed boundary is the delta and the lake bed. The moving interfacial boundary is the overlying water/sediment complex. The overlying water adjacent to the underflow frequently becomes entrained by the underflow current and moves at a velocity almost equivalent to that of the current (Middleton, 1966c).

Stratified flow results from density differences caused by: 1) differences in chemical or mineral composition (for example, fresh water and saline water), 2) temperature differences, or 3) differences in concentration of suspended and/or dissolved sediment (for example, turbidity currents, nuees ardentes).

Numerous studies relating to stratified flow and sedimentation in lakes have been undertaken, both in the laboratory and in the field. Laboratory experiments designed to study density currents in water often utilize tanks or ditches in which slope, dissolved and suspended sediment, temperature, viscosity, and other important variables of

both the influent stream and the standing water are relatively well-controlled. From the behavior of currents in such controlled environments, theories have been proposed regarding the nature of density currents as agents of sediment transport (Bell, 1942; Kuenen, 1950; Middleton, 1966a - 1966c), and interpretation of resulting rates and processes of sedimentation applied to sedimentary deposits in nature (Kuenen, 1950; Kuenen and Migliorini, 1950; Walker, 1967; Shaw, 1975).

Density, or stratified, flow has been studied from various perspectives. Different researchers have looked at density flow in terms of fluid dynamics (Harleman, 1961); temperature differences (Antevs, 1931 and 1951; Mathews, 1956); suspended sediment deposition (Kuenen and Migliorini, 1950; Middleton, 1965 and 1966c); and varve formation (Antevs, 1931 and 1951; Kuenen, 1951; Banerjee, 1973a and 1973b). Antevs (1931) proposed a theory of varve formation based on thermal stratification in glacial lakes. In 1951, he modified and expanded his theory, taking into account further studies on temperature regimes in large glacial lakes. In Antevs' work, temperature differences both between inflowing stream and lake water, and within the lake itself, were the essential criteria for varve deposition. Emphasis was placed on interflow and particularly overflow. Mathews (1956) studied sedimentation in Garibaldi Lake, British Columbia, and its relationship to the physical limnology of the lake water. The results indicated the importance of

thermal stratification in lacustrine sedimentation, at least in large glacial lakes (Garibaldi Lake is over 248m deep). Similarly, temperature differences were found to be the major cause of stratified flow in Bow Lake (Kennedy, 1975).

Unlike Antevs, Kuenen (1951) considered the effects of suspended sediment on density stratification within a glacial lake. During the melt season, the large concentrations of suspended sediment entering many glacial lakes offset the effects of the slight temperature differences, both within the lake, and between the lake and the inflowing stream. This is particularly likely in small lakes. Temperature of maximum density (4°C) may not be reached at any time throughout the year, and water temperatures during the melt season may remain just above freezing. A change in water temperature from 0°C to 4°C raises the density by 0.00013 g/cm³ (Kuenen, 1951). But 2000 mg/l of sediment adds 0.0012 g/cm³ to the density, and concentrations of glacial meltwater streams have been measured as high as 15,000 mg/l (Kennedy, 1975). Furthermore, the quantity of meltwater and concentration of suspended and dissolved sediment may vary greatly - diurnally, seasonally, and annually. There is little opportunity for equilibrium to be established between the lake and the inflowing stream(s) in terms of suspended sediment. Under these conditions, the behavior of the inflowing sediment-laden water and its vertical position within the lake will be determined for the most part by

density differences between stream and lake water due to sediment concentration. When concentrations are low or water temperatures high, stratification due to temperature differences may predominate. Kuenen (1951) stressed the importance of turbidity underflows in glacial lake sedimentation, particularly in terms of varve formation.

Field studies on glacial lakes frequently illustrate the importance of density currents in lacustrine sedimentation. Highly turbid underflows and interflows were found to be the dominant agent of sediment transport and distribution in Lillooet Lake, British Columbia (Gilbert, 1972a and 1975b). Measurements taken included sediment load analysis, current measurements, temperature and transmissivity readings, and bed samples taken with a gravity corer and an Eckman grab sampler. Various types of flow (overflow, interflow, and underflow) at different times of the year apparently caused variation in rates of sedimentation and sediment distribution. Such variations were marked by greater or lesser amounts of sediment in 'traps'; laminations in, and thickness of varves; and mean grain size. From the data collected at Lillooet Lake, it was suggested that low to moderate stream flow resulted in interflow; major floods, such as those due to heavy summer and autumn rain storms, caused major underflows.

Other field studies on glacial lakes include the work of Mathews (1964a and 1964b) on Sunwapta Lake and River, that of Kennedy (1975) on Bow Lake, and that of Smith (1975)

on Hector Lake, all in Alberta. Although his field season was short and his sampling techniques relatively inadequate, Mathews (1964b) demonstrated that Sunwapta Lake is an effective suspended sediment trap. In twenty-four hours (July 22 - 23, 1957), only 0.01 percent to 0.02 percent of the amount of fine-grained material transported into the lake was measured at the outlet, the Sunwapta River. Coarse-grained material, sand and coarse silt, was found only in the southeastern part of the lake, where the major meltwater streams entered. Mathews suggested that "... the bottom topography here [the southeastern part] consisting of a very gentle slope inclined away from the two stream deltas suggests that turbidity currents are locally important in providing the coarser debris." Further work on Sunwapta Lake has also indicated the importance of turbidity underflows (Gilbert, 1975a).

A fairly intensive study was carried out in 1973 on processes of sediment distribution in Bow Lake (Kennedy, 1975). Stream water level and discharge, suspended sediment concentrations in both the lake and stream, rates of sedimentation, lake bottom samples, conductivity and density were measured or calculated. The results indicated the importance of overflow (observed as a milky plume) in the distribution of sediment. Low concentrations of suspended sediment in the glacial stream discharging into Bow Lake were thought to account for the frequency of overflows and the apparent lack of underflows. Kindle (1930), in his work

on Lake Cavell, Alberta, also noted "temporary density segregation" marked by a sharp colour contrast between the sediment-laden glacial stream and the relatively clear lake water. He attributed this to density differences due to differences in suspended sediment concentration. Sediment, or overflow, plumes have been observed in other glacial lakes, such as Lake Louise, Peyto Lake and Sunwapta Lake, Alberta. However, the glacial streams entering Sunwapta Lake have very high suspended sediment concentrations; it is thought that both underflow and overflow occur (Gilbert, 1975a).

Results obtained from studies of density flows have been used to interpret such natural phenomena as "a submerged muddy lake" in an otherwise clear reservoir; thick accumulations of coarse-grained material far out at sea and immediately upstream of dam structures (Bell, 1942); "milky plumes" extending from the mouths of streams (Kindle, 1930; Mathews, 1956; Kennedy, 1975); and graded bedding (Kuenen and Migliorini, 1950; Kuenen and Menard, 1952). Kuenen and Migliorini combined their laboratory and field observations to interpret graded bedding in the Apennines, and construct a possible sequence of events. Further observations and interpretations, as well as those already carried out, can probably be applied to other locations of past and present sedimentation.

1.2 Purpose of the Thesis

Because of its size and its proximity to Athabasca Glacier, Sunwapta Lake is characterized by a large input of sediment and relatively constant temperatures - only slightly above freezing - during the melt season. Such conditions, as suggested by Kuenen (1951), favour lacustrine sedimentation influenced by density stratification due to differences in suspended sediment concentration, rather than by temperature differences, between the inflowing stream water and the standing (lake) water. The purpose of this study is to measure rates of sedimentation and sediment distribution in a small proglacial lake - Sunwapta Lake. From such measurements, it should be possible to determine:

1. The major process, or processes, of sediment distribution active in this lake during the summer of 1975, and
2. By comparison with cores obtained from the lake bed, some indication of recent past processes.

Results obtained in this study could be compared with those found for other glacial lakes.

1.3 Location and General Description of Field Area

Sunwapta Lake is situated about 52° 12' north latitude and 117° 12' west longitude, about 0.4km southwest of the Banff/Jasper Highway in the extreme southern portion of Jasper National Park (Fig. 1). About 8.5km to the east, Sunwapta Pass marks the boundary between Jasper and Banff

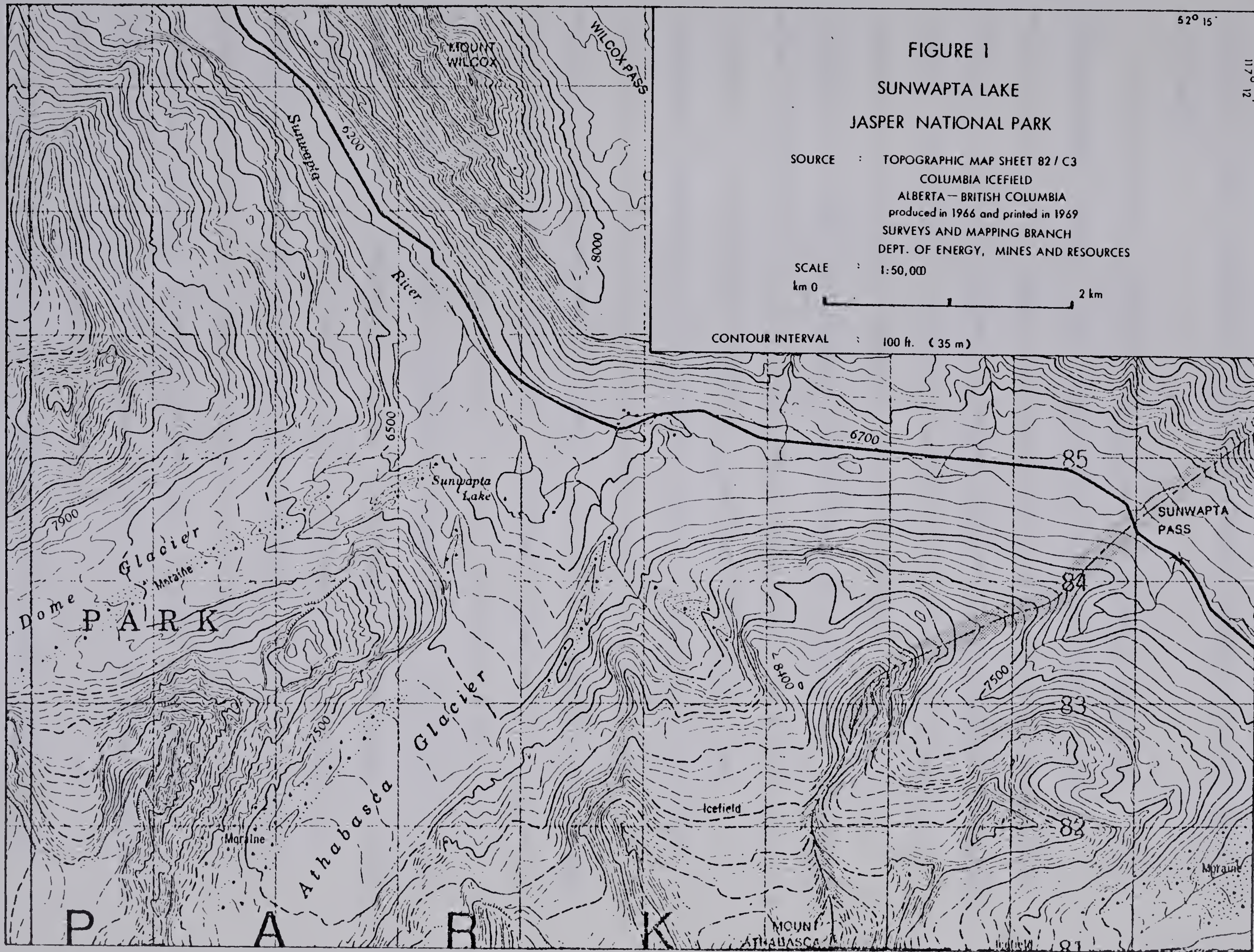


FIGURE 1

SUNWAPTA LAKE

JASPER NATIONAL PARK

SOURCE : TOPOGRAPHIC MAP SHEET 82 / C3
COLUMBIA ICEFIELD
ALBERTA — BRITISH COLUMBIA
produced in 1966 and printed in 1969
SURVEYS AND MAPPING BRANCH
DEPT. OF ENERGY, MINES AND RESOURCES

SCALE : 1:50,000

km 0 — 2 km

CONTOUR INTERVAL : 100 ft. (35 m)

52° 15'

117° 12'

National Parks. Athabasca Glacier forms an outlet glacier tongue of the Columbia Icefield which extends to the south and west.

The bedrock geology comprises massively folded sedimentary rocks, with limestone forming the prominent vertical cliffs. Mountain peaks rise between 3280 and 4200m above sea level. Sunwapta Lake lies at about 1926m. Numerous glacial features - cirques, arêtes, morainal and outwash deposits, U-shaped valleys, hanging valleys - remain as evidence of more extensive glaciation in the past. Sunwapta Lake is situated at what was once the junction of two valley glaciers: a northeast-flowing glacier (of which the Athabasca Glacier is a remnant) and a larger glacier which modified the northwest/southeast-trending valley now occupied by the Sunwapta River. The latter glacier has long since disappeared, while the Athabasca Glacier is apparently still retreating. In the last thirty to forty years, the frontal margin of the Athabasca Glacier has retreated about 2400m. Morainal deposits cover the valley floor north of the present toe of the glacier, and previous stillstands are marked by prominent recessional moraines. Lateral moraines border the east and west sides of the glacier and extend beyond the present glacier terminus. Former tributary glaciers on Mt. Athabasca have been left as hanging glaciers (Baird, 1966; Harrington,1970).

Mountains enclose the glacier in a semi-circle, from Mt. Athabasca (4167m) on the east; Andromeda Mtn. in the

southeast; the rock wall to the south over which flows the massive icefalls; the Snow Dome (4128m) to the southwest; to the bedrock ridge on the west separating Athabasca Glacier from Dome Glacier. To the north, across the Sunwapta River Valley, Mt. Wilcox rises to 3443m.

At the toe of Athabasca Glacier, the old moraines and outwash deposits of the glacier have caused ponding of glacial meltwater, and, since 1935, the creation of a small proglacial lake (Fig. 2). A proglacial lake is usually defined as a lake "occupying a basin in front of a glacier generally in direct contact with the ice." The source waters of the lake - Sunwapta Lake - are primarily small meltwater streams; its outlet, the Sunwapta River. The lake has increased in area with the retreat of the Athabasca Glacier (Reid and Charbonneau, 1972 and 1975). In 1945, for example, over two-thirds of the present lake area lay under the glacier ice. The area of the lake in 1957 was determined to be 0.13km², and its maximum depth was between twelve and fifteen metres. By 1960, the surface area of Sunwapta Lake was about 0.16km². The glacier still formed the southern boundary, and calving along the ice margin created small icebergs during the melt season. At present, a narrow band of moraine and outwash deposits and moraine-covered ice separates the lake from the visible ice margin. In 1975, with the continuing growth of active deltas, the lake was about 0.145km² in area.

The lake is divided into two basins by a

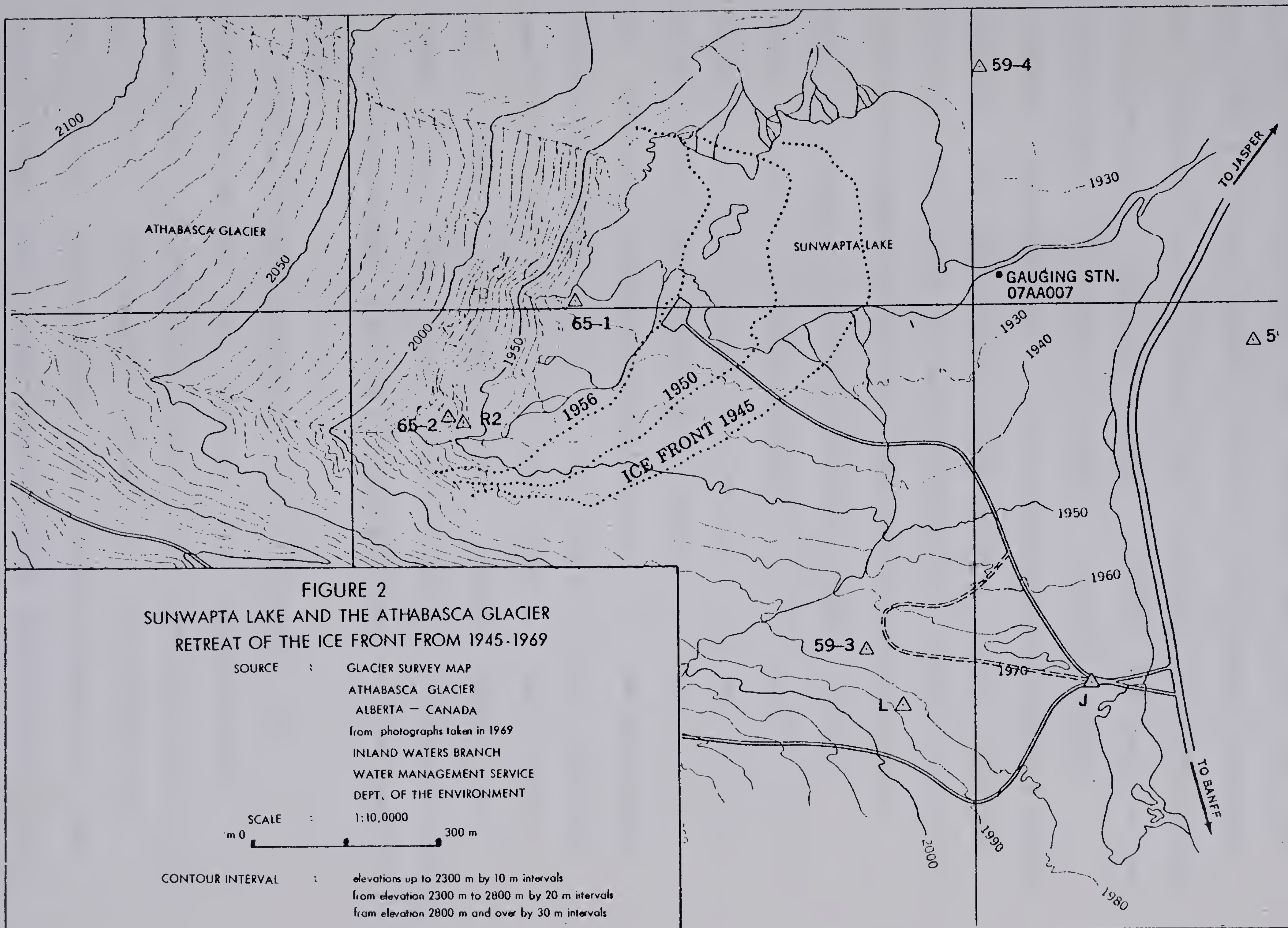


FIGURE 2

SUNWAPTA LAKE AND THE ATHABASCA GLACIER

RETREAT OF THE ICE FRONT FROM 1945-1969

SOURCE : GLACIER SURVEY MAP
ATHABASCA GLACIER
ALBERTA – CANADA
from photographs taken in 1969
INLAND WATERS BRANCH
WATER MANAGEMENT SERVICE
DEPT. OF THE ENVIRONMENT

SCALE : 1:10,0000

m 0 — 300 m

CONTOUR INTERVAL : elevations up to 2300 m by 10 m intervals
from elevation 2300 m to 2800 m by 20 m intervals
from elevation 2800 m and over by 30 m intervals

moraine-covered bedrock ridge trending west/east (Fig. 3). The ridge forms an island flanked by two shallow channels, about 6m deep on the west side and 4m deep on the east side. The larger basin, the north basin, is about 11m deep in the deepest section. On the east shore, a stream flowing northwest from a glacier on Mt. Athabasca has built a delta into the lake. The smaller basin reaches a depth of about 10m. The south basin is being noticeably reduced in area by the active growth of deltas, since the major sources of water and sediment are the meltwater streams flowing directly from the Athabasca Glacier into the south part of the lake. In 1974, the major source of water and sediment was the stream from the moraine-covered ice west of the lake, forming the southwest delta. In 1975, the southwest stream was largely inactive; the dominant stream was that flowing from the glacier into the southeast part of the lake, forming the southeast delta. It seems likely that changes within the glacier's internal drainage system result in the predominance of either the southwest or the southeast stream.

Because of its proximity to the glacier, the temperature of the lake water, as well as atmospheric temperature, is affected by ice-contact and katabatic winds. The higher the atmospheric temperature, the greater the effect of the cold katabatic winds sweeping north off the glacier. Lake water temperatures remain only slightly above freezing throughout the melt season; in fact, ice may form

FIGURE 3

BATHYMETRIC MAP OF SUNWAPTA LAKE
AND
REPRESENTATIVE PAN SITES

SOURCE: 1974 SURVEY (GILBERT, 1975a)

SCALE : 1cm : 15.6m

LEGEND

1 - THE PROXIMAL ZONE
2 - THE EAST CHANNEL
3 - THE WEST CHANNEL
4 - THE DEEPEST SECTION OF THE LAKE
5 - THE DISTAL ZONE

isobath interval : 1m

Reference (0m depth) is Water Survey Stage of 3 feet at Sunwapta outlet

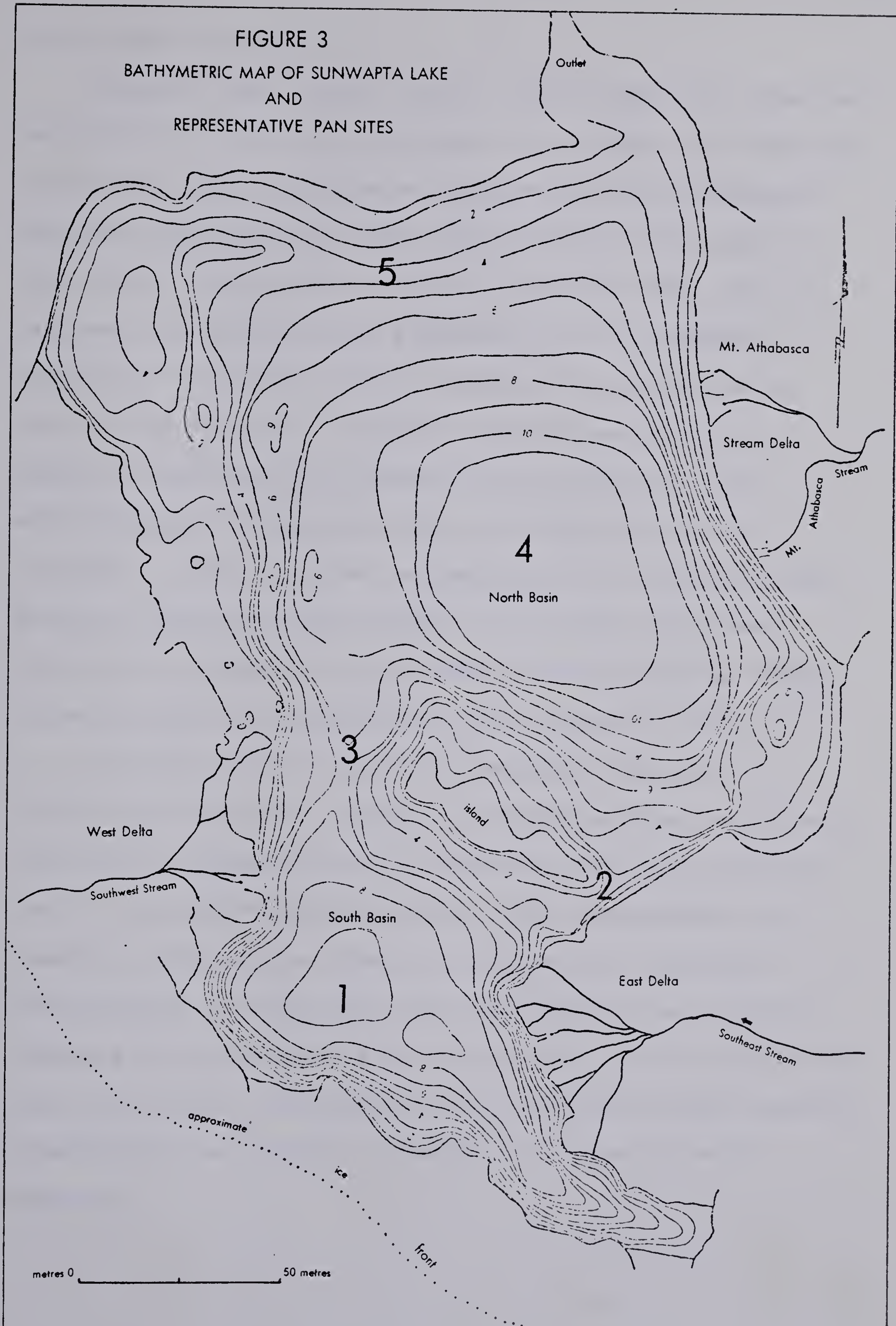


FIGURE 3
BATHYMETRIC MAP OF SUNWAPTA LAKE
AND
REPRESENTATIVE PAN SITES

on the lake in summer.

Sunwapta Lake forms a small, fairly shallow, relatively well-defined study area. Sediment is carried into the lake largely by glacial meltwater streams from the Athabasca Glacier, generally with one stream dominant throughout a melt seaon. Streams flow directly into the lake with no intermediate ponding and, therefore, no intermediate trapping of sediment. Little sediment is introduced by non-glacial streams - a factor aiding measurement of sedimentation rates and processes. Furthermore, the effectiveness of Sunwapta Lake as a sediment trap is conducive to the study of sedimentation in a glacial lake. Major preliminary field studies of Sunwapta Lake have already been carried out (Mathews, 1964b; Gilbert, 1975a), and equipment was tested during the summer of 1974.

Sunwapta Lake is readily accessible from the Banff/Jasper Highway. However, although boating is allowed, the lake is apparently not a favourite with park visitors due to its muddy-coloured waters, cold temperature, and somewhat unattractive (that is, unforested) immediate surroundings. In addition, the local climate is directly affected by the proximity of the glacier. Field work in the area, therefore, was generally not hindered by such tourist interference as boating, swimming and tampering with equipment.

2. Methodology

2.1 General

Conclusions regarding the process or processes of sedimentation within a lake require investigation of the rates of sedimentation and the distribution of suspended sediment throughout the lake. Experiments and observations have shown these two factors to be a function of the sedimentation process: overflow, interflow or underflow (Kindle, 1930; Antevs, 1931 and 1951; Bell, 1942; Kuenen, 1950 and 1951; Kuenen and Migliorini, 1951; Mathews, 1956; Middleton, 1966a - 1966c; Gilbert, 1972 and 1975b; and Kennedy, 1975). Overflow plumes are a visible indicator of sediment movement in a standing water body (Kindle, 1930; Mathews, 1956; Kennedy, 1975). Interflow and underflow movements of currents and sediment, being subsurface processes, are rarely observed. The presence of one or more types of flow must often be inferred from relative sediment concentrations and sediment distribution patterns studied in the field. Unfortunately the 'controlled environment' of an experiment is not duplicated in nature. In flumes, for example, temperatures, densities, viscosity and sediment concentrations can be adjusted or held constant for long periods of time. Certain properties may be selected for study. In the natural environment the number of variables affecting sedimentation, their relative importance, and the degree to which they interact are largely beyond measurement

by present field techniques.

Field work is necessary to reveal the similarities and discrepancies between experiment and reality. Unfortunately, field work is restricted. For example, although sediment deposition is not limited to the melt season, the cold weather, lake ice and lack of suitable equipment restricts field study of most proglacial lakes to the summer months.

From July 2 to August 21, suspended and bottom sediment samples were collected from selected sites in Sunwapta Lake (as described below). Spring break-up occurred about May 15, but field work did not commence until July 1. This was a result of delays in obtaining equipment and arranging living accommodations. A field camp was established and some preliminary work done between June 20 and June 23. A rented trailer was located in the Brewster Staff Camp area and served as both living quarters and field laboratory. The field laboratory was set up for preliminary weighing, drying and analysis of the samples; dry samples were taken to Edmonton for further analysis in the physical laboratory of the Dept. of Geography, University of Alberta. On the island in Sunwapta Lake, a small shed was placed to protect sensitive equipment from weather and tourist damage. A small aluminum row boat was used on the lake. Poor weather, including heavy snowfall, ended the field season on August 21.

2.2 Field Methodology

2.2.1 Site Selection

Initial field work in June included selecting sampling sites in Sunwapta Lake. A bathymetric map based on 1973 echo sounding data was used to select general sampling locations representative of various parts of the lake (see Figure 3):

1. The proximal zone - the south basin, where the major source of water and suspended sediment discharged into the lake. In 1974, the southwest stream was the major source; in 1975, the southeast stream. The south basin was also the area most likely to be affected by underflows (Antevs, 1951; Gilbert, 1972 and 1975a).
2. North of the east channel. This was the shallower channel, about two to three metres deep. Flow between the south and the north basins was constricted between the island and the southeast delta, the most active delta in 1975.
3. North of the west channel. This channel was wider and deeper than the east channel. The lake bed within this channel was relatively steep and irregular.
4. The deepest (about 11m) part of the north basin and of the whole lake.
5. The distal zone - the relatively shallow (4.5 - 5m) northern part of the north basin. In the distal zone of large lakes, settling of fine material from suspension is generally assumed to be the dominant or only process of sedimentation (Antevs, 1931 and 1951; Kuenen, 1951;

Mathews, 1964b).

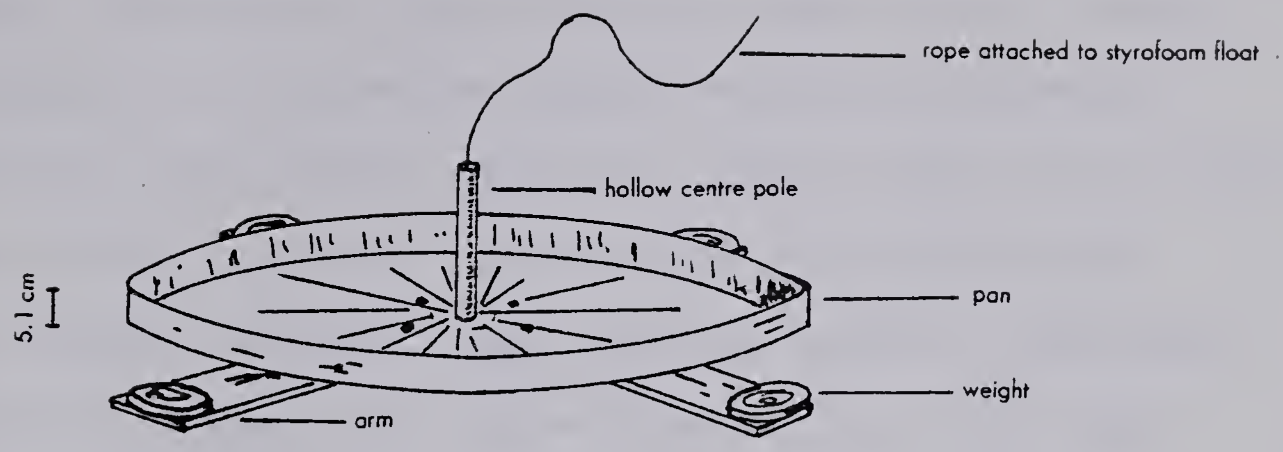
In addition, sampling was carried out regularly in the southeast stream and less frequently in the southwest stream and at the lake outlet, the Sunwapta River.

Two major types of sediment sampling were conducted at these lake sites:

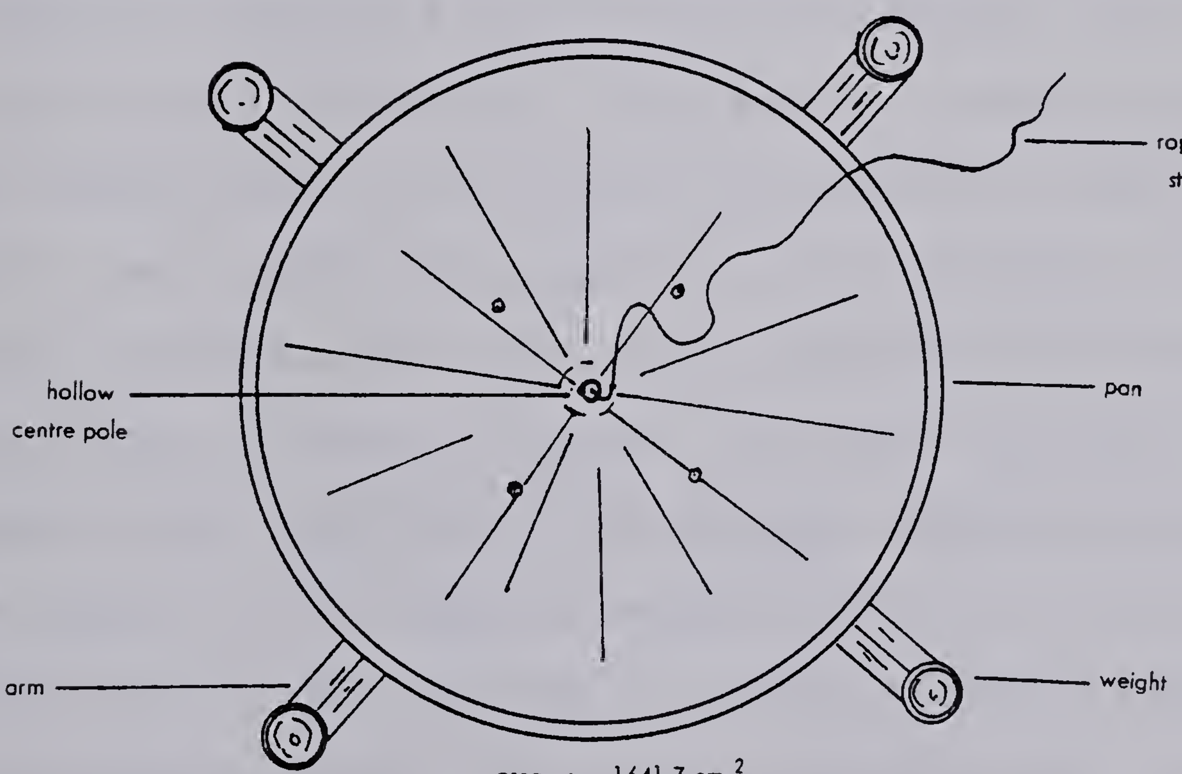
1. Sampling of suspended sediment in surface and subsurface water, and
2. Sampling of sediment settling out or otherwise deposited on the lake bed.

2.2.2 Sampling of Bottom Sediment

Two types of sediment pans or traps were employed to collect sediment deposited on the lake floor. Seven large sediment pans and four smaller cake pans were placed in the lake. The large sediment traps were based on a new Swedish design, with a collecting area of 1641.7cm^2, and sides about 5cm high. Each circular pan was attached at the base to four folding 'arms' with weights (Fig. 4). The combined weight of the arms, the weights, and the pan was thought sufficient to prevent disturbance by normal currents and to reduce possible disturbance by slumps and underflows. In the centre of each pan, one end of a guide rope was attached to a vertical pole. While the pan rested on the lake bed, the guide rope was tied to a styrofoam float at the surface marking the position of the pan. The weights on the pan arms



SIDE VIEW



area : 1641.7 cm ^{2}

TOP VIEW

FIGURE 4
SEDIMENT PAN

were necessary to counteract the force of wind-generated waves and wind-driven ice on the surface float.

Before recovery of each sediment pan, a small marker float anchored to a rock was placed nearby. A circular plexiglas lid was lowered along the guide rope onto the open sediment-filled pan (Fig. 5). The lid reduced loss of sediment during recovery. Each pan was taken to shore and its contents emptied into large plastic jars with lids. After emptying, the open pan was returned as nearly as possible to its original position in the lake.

This model proved both heavy and cumbersome. Recovery by hand of each sediment pan with the additional weight of the sediment required a great deal of strength, particularly for those pans in deep (10 - 11m) water. A winch, pulley and tripod system would have reduced the amount of labour involved, but neither the equipment nor a suitable boat or raft was available. The pans, being circular and heavy, were also difficult to empty. However, the major problem was the lowering of the lid down to the open pan without dragging and/or upsetting the pan, an awkward procedure in all but very calm water. The boat had to remain stationary while the lid was dropped and the pan raised; unfortunately, an anchor could not be used each time because:

1. It would have disturbed bottom sediment,
2. It might have landed on a pan, and
3. It would have been impossible to raise without rocking the boat and perhaps upsetting the sediment-filled pan

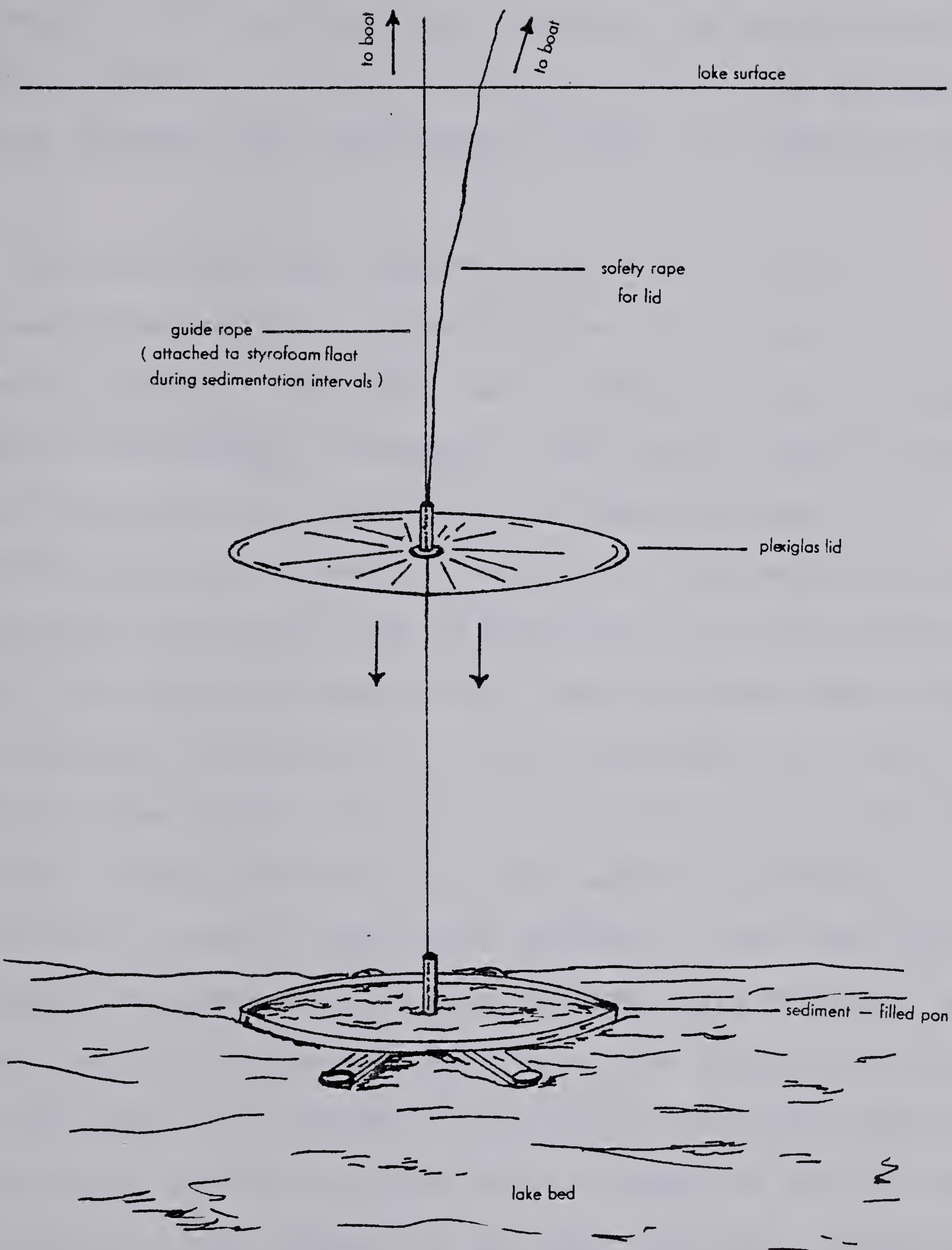


FIGURE 5
RECOVERY OF SEDIMENT PAN USING PLEXIGLAS LID

resting on the stern.

Calm or near-calm conditions were relatively rare in July and August, 1975, and the pans could not be brought up at regular intervals. A record was kept of the time periods between recovery and replacement of each pan (Table 1A and 1B).

Sediment pans were placed at each of the five representative sites in Sunwapta Lake. Three pans (A, B, and C) were located in the south basin. Since the major inflow of water and sediment occurred in the basin, deposition into these three pans was expected to be high. Sediment concentrations were known to be high and the possibility of underflows had already been investigated in 1974 (Gilbert, 1975a). In the north basin, Pan 1 was situated north of the west channel, the deeper of the two channels. Pan 2 was placed in the deepest section of the lake; Pan 3, north of the east channel; and Pan 4, in the north, or distal, portion of the lake. These pans remained in the same general locations from June 23 to August 21 (Fig. 6). In order to place a pan in the deepest section of the lake and to ensure that all pans were placed on relatively flat areas away from steep slopes (potential slump zones), lake bed profiles were taken with an echo sounder in the west and east channels and in the centre of the north basin. Pans 1 and 3 were not placed directly in the channels because of the steep, irregular lake bed at these locations.

The second type of sediment trap used was a small

Table 1a. Time intervals between placement and recovery of large sediment pans.

Pan	Location	From	To
1	north of west channel	Jun 20	0910 Jun 23
		0930 Jun 23	0930 Jul 5
		1000 Jul 5	2115 Jul 14
		2200 Jul 14	1030 Jul 23
		1045 Jul 23	1045 Aug 2
		1100 Aug 2	1235 Aug 8
		1250 Aug 8	1500 Aug 21
2	deep section of north basin	Jun 20	0830 Jun 23
		0845 Jun 23	0945 Jul 4
		1015 Jul 4	1030 Jul 17
		1100 Jul 17	1445 Jul 25
		1510 Jul 25	1050 Aug 3
		1115 Aug 3	1605 Aug 8
		1620 Aug 8	1040 Aug 18
		1055 Aug 18	1030 Aug 21
3	north of east channel	Jun 20	0850 Jun 23
		0900 Jun 23	0920 Jul 3
		1000 Jul 3	1030 Jul 15
		1115 Jul 15	1030 Jul 25
		1045 Jul 25	1100 Aug 1
		1105 Aug 1	1100 Aug 8
		1115 Aug 8	1435 Aug 21
4	north (distal) end of lake	Jun 21	0930 Jun 22
		0945 Jun 22	2155 Jul 6
		2215 Jul 6	1110 Jul 17
		1125 Jul 17	1025 Aug 3
		1040 Aug 3	0940 Aug 21

Table 1b. Time intervals between placement and recovery of large sediment pans.

Pan	Location	From	To
A	south basin	1730 Jun 20	1030 Jun 22
		1030 Jun 22	0910 Jul 3
		2050 Jul 14	1600 Jul 19
		1620 Jul 19	1050 Jul 25
		1110 Jul 25	1200 Aug 3
		1215 Aug 3	1135 Aug 8
		1200 Aug 8	1034 Aug 21
A	south basin	1000 Jun 23	1050 Jul 4
		1115 Jul 4	1010 Jul 15
		1030 Jul 15	1015 Jul 21
		1030 Jul 21	1030 Jul 26
		1045 Jul 26	1135 Aug 3
		1150 Aug 3	1130 Aug 8
		1135 Aug 8	1105 Aug 18
		1120 Aug 18	1515 Aug 21
C	south basin	1745 Jun 20	0940 Jun 23
		0940 Jun 23	1015 Jul 4
		1040 Jul 4	1040 Jul 15
		1100 Jul 15	1040 Jul 21
		1100 Jul 21	1100 Jul 26
		1120 Jul 26	1110 Aug 2
		1120 Aug 2	1155 Aug 8
		1220 Aug 8	1100 Aug 21

FIGURE 6

LOCATION OF SEDIMENT PANS AND CORES

SOURCE: 1974 SURVEY (GILBERT, 1975a)

SCALE : 1cm : 15.6m

LEGEND

● 1	-	SEDIMENT PAN
○ 1A	-	'CAKE' PAN
⊠ 2	-	CORE SITE
◇	-	1974 SURVEY MARKER

CHANGES IN THE LOCATION OF MAJOR SOUTHEAST STREAM CHANNELS , SUMMER 1975:

— —	-	JUNE 20
- - - -	-	JULY 4
——	-	JULY 6
-·-·-	-	JULY 20
▬	-	'PERMANENT' CHANNEL

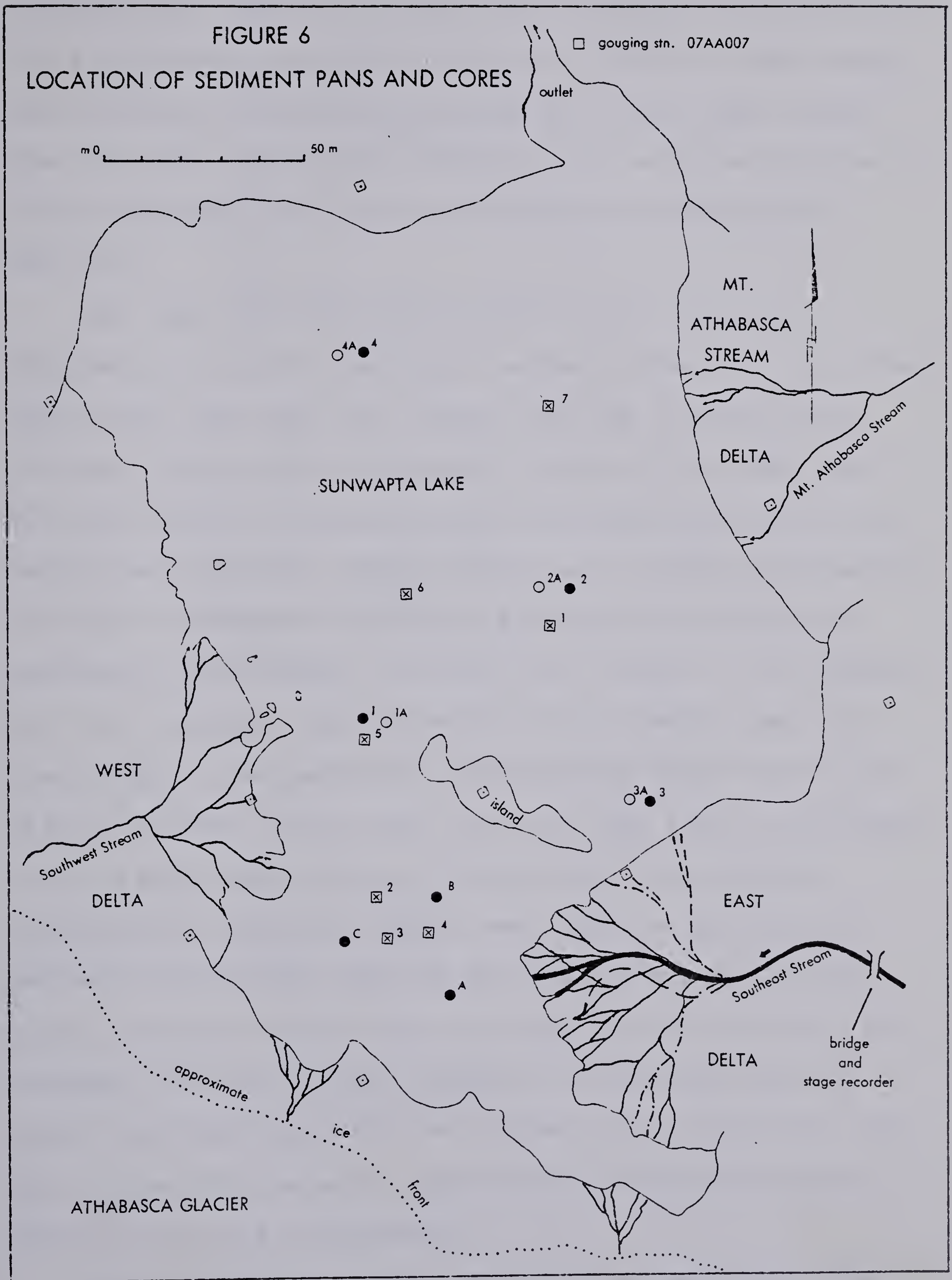


FIGURE 6
LOCATION OF SEDIMENT PANS AND CORES
gouging stn. 07AA007
outlet
m 0
50 m
MT.
ATHABASCA
STREAM
DELTA
Mt. Athabasca Stream
SUNWAPTA LAKE
4A
4
7
6
2A
2
1
1
1A
5
island
3A
3
WEST
Southwest Stream
DELTA
2
B
C
3
4
A
EAST
Southeast Stream
DELTA
bridge
and
stage recorder
approximate
ice
front
ATHABASCA GLACIER

square cake pan. Each pan had a collecting area of approximately 400cm² and sides about 5cm high. One exception was a replacement pan with an area of 289cm². A lead weight was attached to the bottom of each pan. Wires were looped from the four corners and joined in the centre of the pan; a string connected the wire to a surface styrofoam float (Fig. 7).

The cake pans (1A ,2A, 3A and 4A) were used to supplement and check the larger sediment pans (1 - 4) in the north basin (see Fig. 6). Placed from two to four metres from each large pan, the attached floats of the cake pans were also useful as markers when the larger pans were being emptied and replaced. These smaller pans proved satisfactory in terms of sediment collection and ease of handling. In relatively calm weather, each pan was brought to the surface and into the boat, emptied rapidly into plastic jars, and lowered back into position - an operation requiring ten to fifteen minutes. If the boat could be kept fairly stationary during ascent, the weight of the pan and its contents prevented the pan from tipping over. Little wash-out of sediment was evident when the pan was raised slowly. The square shape and light weight of the pans made emptying the sediment relatively easy. Instead of taking each pan to shore, the operation could be carried out in the boat; this was a valuable time-saver, particularly when calm periods often lasted only a few hours.

Unfortunately the light weight of the pans made them

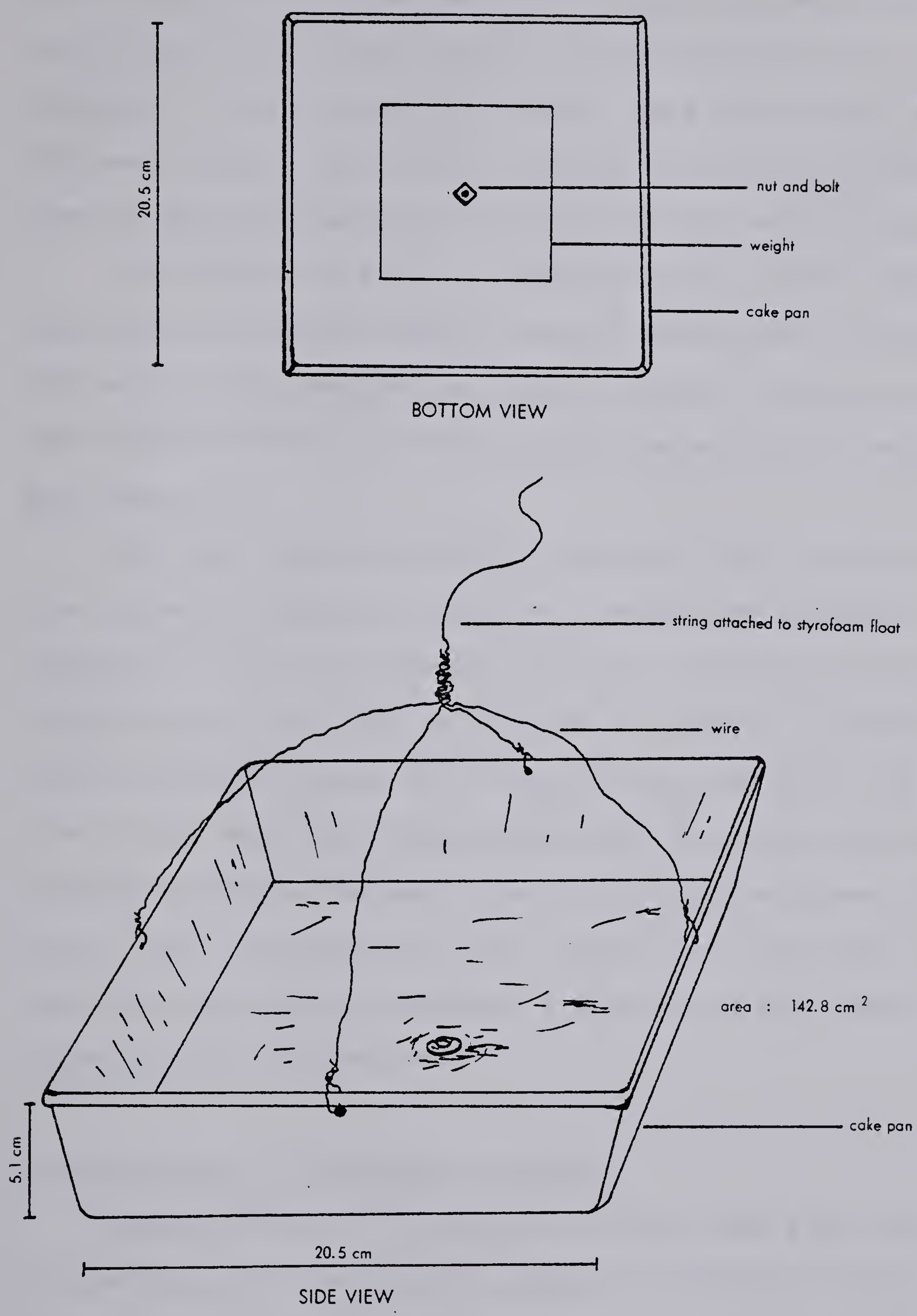


FIGURE 7
SEDIMENT (CAKE) PAN

susceptible to disturbance. Several cake pans were lost or moved when the attached floats, because of unusually strong currents or wind-blown ice, dragged them into deeper water. Sediment samples were never obtained from Pan 3A although several cake pans were placed north of the east channel.

The absence of a lid and the necessity of the boat remaining stationary during recovery restricted raising of the pans to calm weather periods. A record was kept of the time intervals between recovery and replacement of each cake pan (Table 2).

The high sides of both the sediment pans and the cake pans probably disrupted sediment movement by currents adjacent to the bed. However, material settling out from suspension or deposited by all but the deepest currents would have been caught in the open pans. The sides, on the other hand, may have reduced wash-out of sediment in the pan by deep currents. Sediment from each trap was poured into one or more large plastic jars. These jars were then sealed, labelled (date and pan number) and taken to the field laboratory or to Edmonton.

2.2.3 Sampling of Suspended Sediment

Concentrations of suspended sediment may vary both horizontally and vertically. Sampling bottles or 'milk bottles' were used to obtain surface samples in the lake. Each 450cm^3 glass bottle had a permanent label and a snap-on, spill-proof lid. Samples were collected by hand; a

Table 2. Time intervals between placement and recovery of small sediment (cake) pans.

Pan	Location	From	To
1A	near Pan 1, north of west channel	0920 Jul 5 0950 Jul 14 1140 Jul 21 1230 Aug 3	0940 Jul 14 1135 Jul 21 1220 Aug 3 1455 Aug 21
2A	near Pan 2, deep section of north basin	0930 Jul 5 0940 Jul 12 1115 Jul 20 1020 Aug 13	0915 Jul 15 1115 Jul 20 pan lost 1420 Aug 21
3A	near Pan 3, north of east channel	0940 Jul 9 1010 Jul 25	pan lost pan lost
4A	near Pan 4, north (distal) end of lake	2150 Jul 6 1040 Jul 14 1020 Jul 22 1045 Aug 3	1030 Jul 14 1015 Jul 22 1042 Aug 3 1422 Aug 21

bottle was lowered on its side 2 - 3cm into the lake and about 300 - 400cm³ of water allowed to flow into the bottle as the boat drifted. The bottle was then sealed and marked with the date, time and location of the sample. Bottles were transferred from the lake to the field laboratory in compartmentalized boxes.

Because of the relative ease of handling, surface samples could be obtained on a fairly regular basis, usually in the morning and late afternoon/early evening. Sampling was carried out from July 2 to August 21. The styrofoam floats attached to the sediment pans and marking their positions were also used to mark sites for suspended sediment sampling. In this way it was hoped that suspended sediment concentrations at the surface could be related to amounts of sediment settling out in the sediment pans. Fairly regular surface water samples were taken in the vicinity of Pans 1, 2, 3 and B; less regular samples at Pan 4. Pan 4 site, the distal (north) end of Sunwapta Lake, was usually difficult to sample because of the prevailing katabatic wind. The wind was from the south and the boat had to be returned to the south end of the lake, a tiresome and time-consuming business against the wind and waves. For this reason, the Pan 4 site was not sampled as regularly as were the more accessible sites near Pans 1, 2, 3 and B. Samples were also collected about two or three times a week from the lake outlet.

For subsurface samples, a Van Dorn bottle proved

satisfactory. The 'bottle', a heavy plastic cylinder open at both ends, was lowered to the desired depth where a messenger (a short metal pipe) was used to trigger the release of two suction cups. The cups closed the open ends of the cylinder, trapping a sample of water and sediment at that depth (Fig. 8). Samples were generally taken at vertical intervals of 2m as marked off on the attached rope. However, within the east and west channels, the interval was reduced near the lake bed to allow for the shallow water depths. Each sample was brought to the surface and emptied into a bottle. The bottles were labelled and transferred to the field laboratory.

Subsurface samples were collected far less frequently and less regularly than surface samples. Unlike surface sampling, relatively calm weather was necessary in order not to drift too far from the sampling site. Sampling was carried out in the east and west channels, in the centre of the north basin, and in the south basin (Table 3). A depth-integrating sampler for lakes would have produced a more complete vertical average of sediment concentration from surface to bed.

Regular morning and late afternoon suspended sediment samples were also collected from the southeast stream. The tourist bridge made the middle of the main stream channel accessible for depth-integrating samples (Stichling and Smith, 1968). An open 'milk bottle' was clamped into a depth-integrating sampler attached to a sampling rod

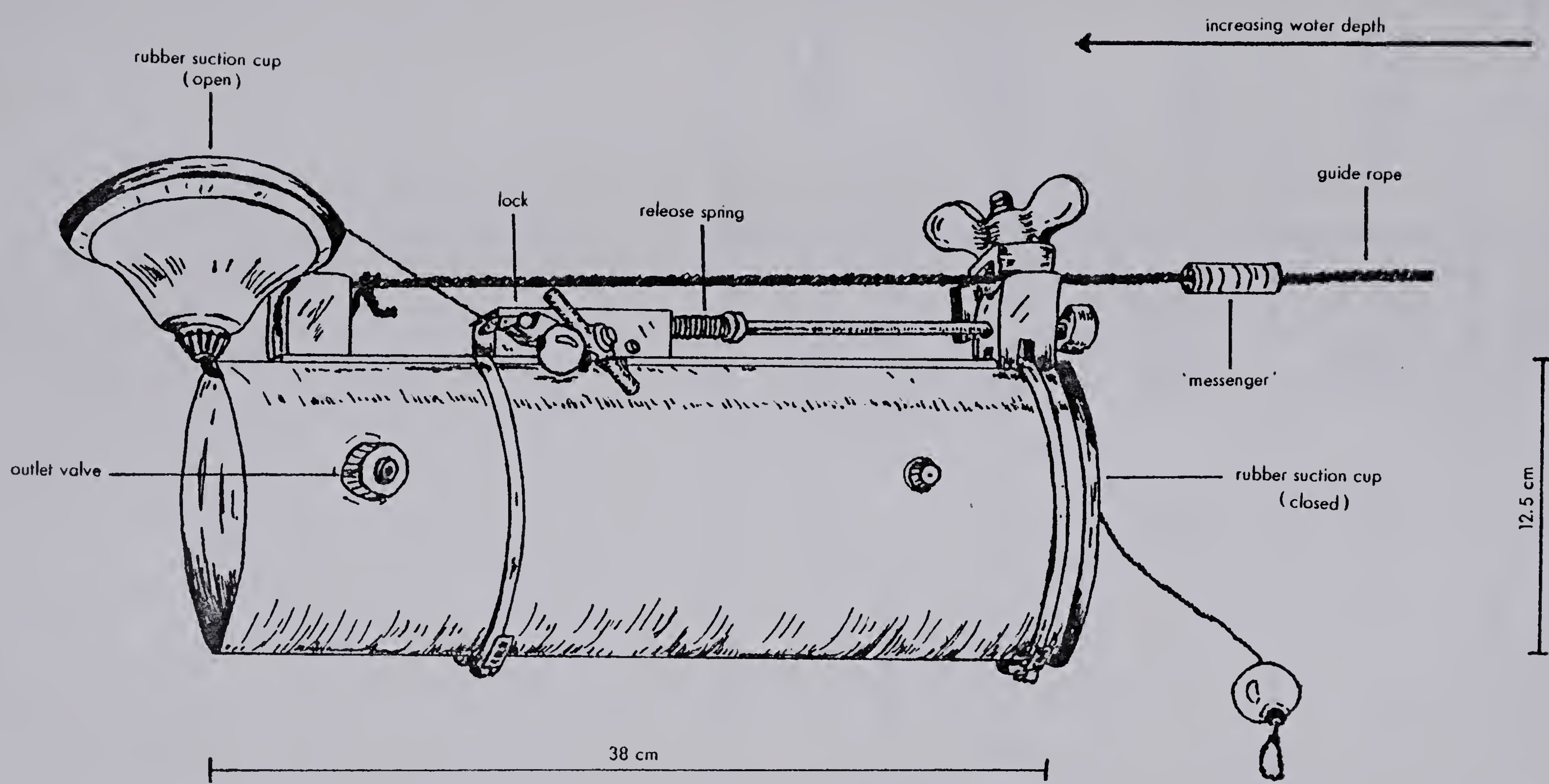


FIGURE 8
VAN DORN BOTTLE SAMPLER

Table 3. Van Dorn bottle samples.

Location	Date	Depth of samples meters
west channel - south of pan 1	10 Jul 17 Jul 22 Jul	1.5, 3.1, 4.6 2, 4 2, 4, 5
east channel - south of pan 3	10 Jul 17 Jul 22 Jul	1.5, 3.1 2, 3 2, 4
deep section of north basin - near pan 2	19 Jul 22 Jul	2, 4, 6, 8, 10 2, 4, 6, 8, 10
south basin near pan B	17 Jul	2, 4, 6, 7

(Fig. 9). About 350cm^3 of water were required for a representative sample. If too little water and sediment were collected, the procedure was repeated. If the bottle was too full or did not reach the bed, the bottle was emptied and washed out, and the sample retaken. Each sample bottle was labelled and taken to the field laboratory.

About once or twice a week, similar samples were collected from the southwest stream. Samples were obtained by wading into the stream; there was no fixed sampling point. Because of the relative inactivity of this stream in 1975, sampling and other measurements were largely confined to the southeast stream. This was the reverse of the procedure in the field season of 1974 (Gilbert, 1975a).

An attempt to measure suspended sediment concentrations through use of a transmissometer failed. The instrument proved too sensitive for the highly turbid waters of the lake, except for areas of groundwater inflow along the shore. As will be discussed below, transmissivity, measured by means of a transmissivity kit, was found to correlate with suspended sediment concentrations.

2.2.4 Current and Velocity Measurements

Suspended sediment distribution in a lake is partly a function of the characteristics of the inflowing stream(s), including suspended and dissolved sediment concentrations, temperature and discharge. In 1975, the major stream flowing into Sunwapta Lake entered from the southeast. Daily

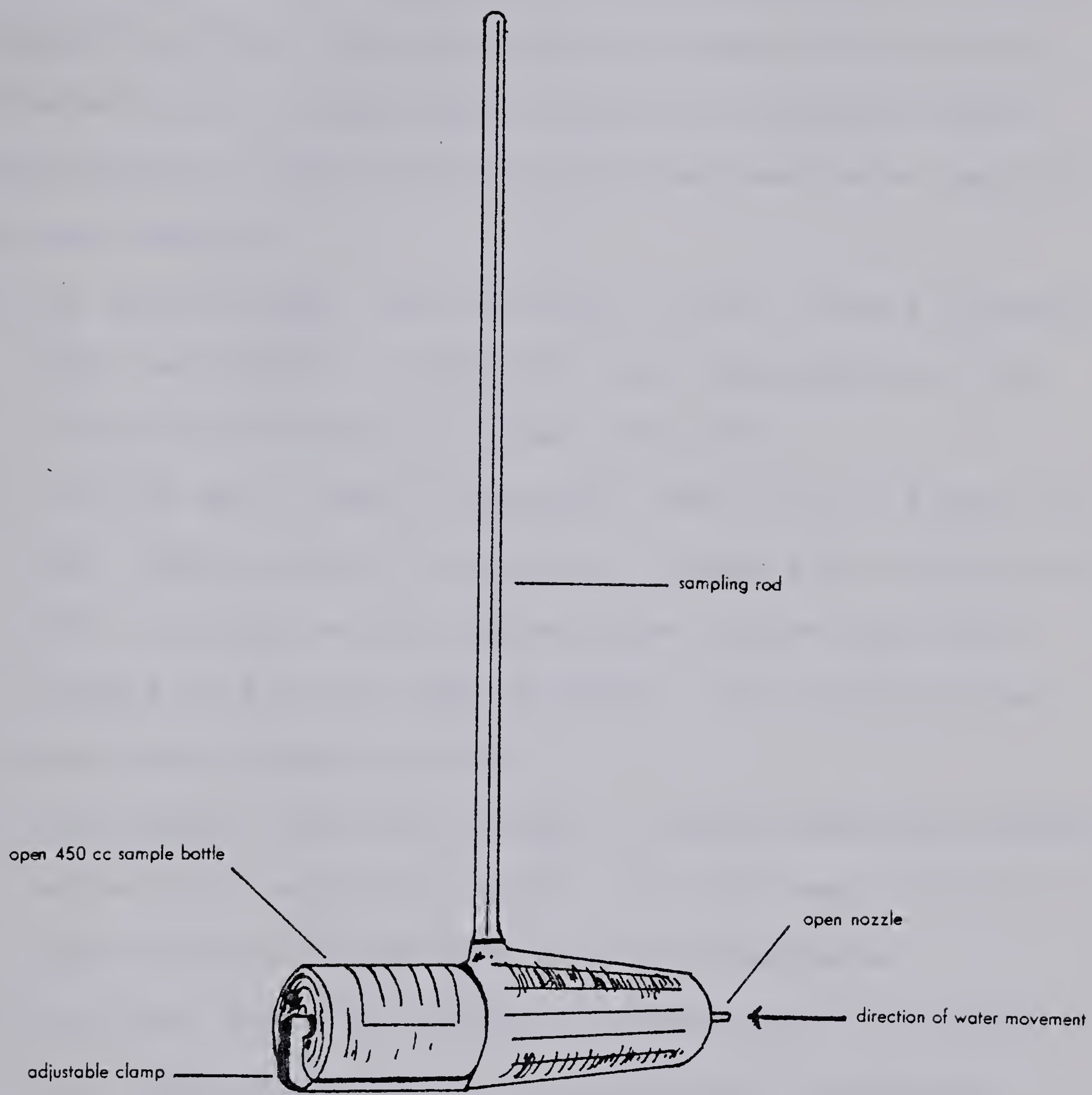


FIGURE 9
DEPTH INTEGRATING SAMPLER

(morning and afternoon) variations in suspended sediment concentration were sampled with a depth-integrating sampler. Dissolved sediment concentrations of stream samples were estimated with a conductivity meter, as discussed below. Temperatures of both the stream and the lake water were not measured because:

1. The major stream, the southeast stream, flowed directly from the glacier to the lake; the temperature of the water was assumed to be just above 0°C.
2. The lake was a small proglacial lake, only 0.145km² in area, fed by glacial meltwater streams and affected by cold katabatic winds. Temperatures in the lake were assumed to be just above freezing, with little or no variation across the lake.
3. Instruments sensitive enough to measure possible slight temperature variations within the lake and between the major stream and the lake were not available.
4. The large input of suspended sediment made it unlikely that temperatures would be significant in sediment distribution in the lake.

Two stage-discharge rating curves were constructed for the southeast stream (Fig. 10 and Appendix B). Discharge was plotted against water stage, that is "... the height ... of the surface of the water above an arbitrary datum" (Morisawa, 1968). Discharge is "... the volume of water flowing through a cross-section of the stream channel per unit time, measured in cubic feet per second" or cubic

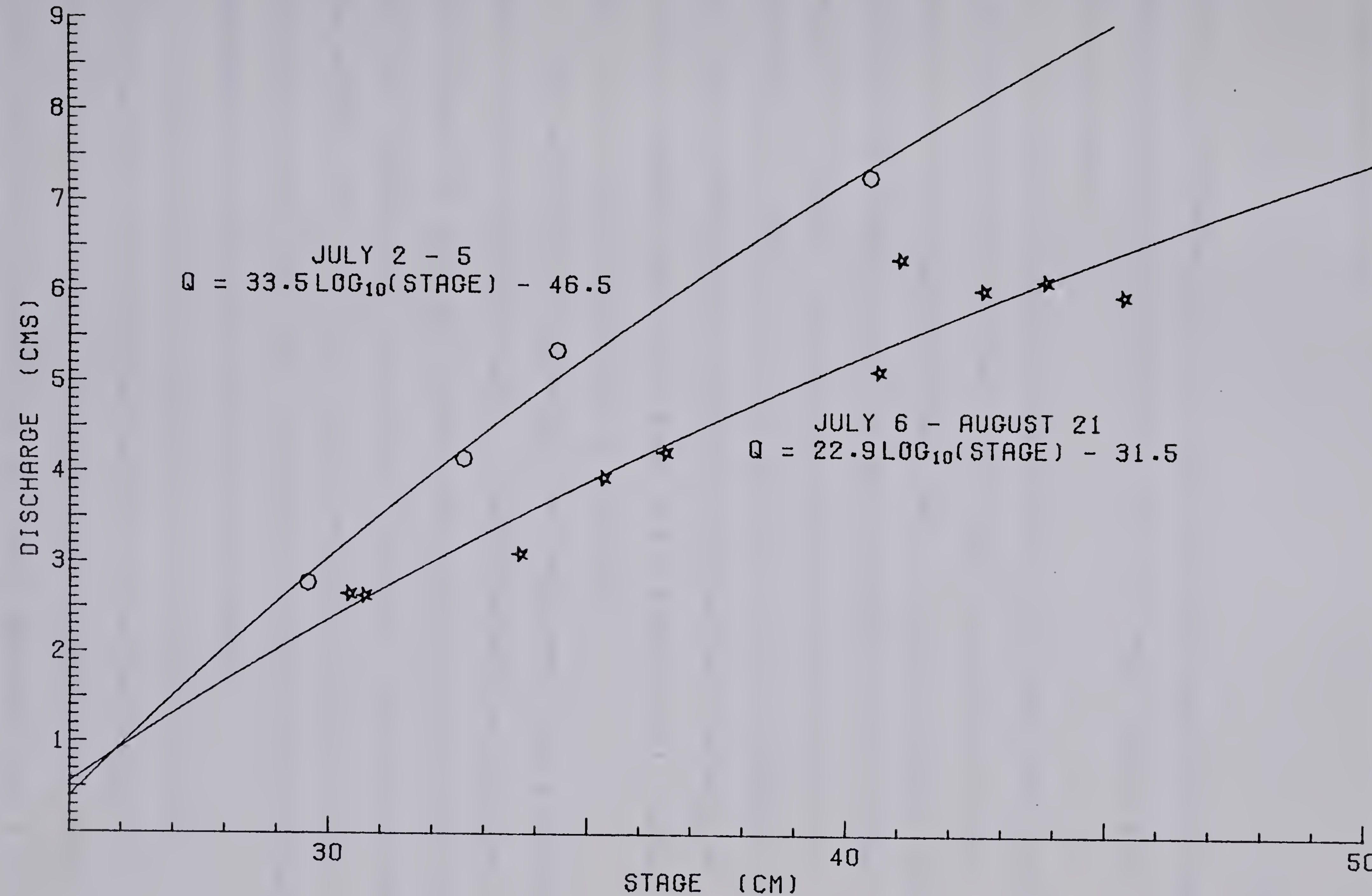


FIGURE 10. RATING CURVES FOR DISCHARGE (Q) VERSUS STAGE.

metres per second (Morisawa, 1968). Discharge is calculated using the equation:

$$Q = A\ V \tag{2-1}$$

where Q is discharge, A is cross-sectional area of the part of the channel being measured, and V is mean velocity at that section.

The width of the main channel of the southeast stream was fixed at about 25 feet (about 8m) by concrete walls supporting the tourist bridge. Here, a small portable stage recorder and wooden stilling well fastened to the bridge supplied an almost continuous record of water height in centimetres. High and low periods of flow were apparent on the chart, particularly diurnal fluctuations. On July 9, vandals tampered with the float and balance wheel, making the record less reliable for a few days.

The velocity of the stream was measured with a Gurley current meter and stop watch. A tape measure was fastened to the bridge and stretched across the width of the stream. At two-foot (0.64m) intervals along the tape, the current meter was lowered to 0.6 of the depth. The mean velocity of the southeast stream was then calculated from the total velocity measurements across the width of the stream.

A stage-discharge rating curve was drawn for July 2 - 5 based on four velocity/area surveys. From the rating curve it was possible to read the discharge for any water height. Stream velocity was monitored ten times between July 6 and

August 21. A hot spell with air temperatures about 26.8°C lasted for the first two weeks in July. Stream levels were high, the southeast delta was flooded, and the lake level was 0.3 - 0.5m higher than it was in August. The remainder of the summer was generally cool, windy and wet. Both stream and lake levels fluctuated widely. The large quantities of sediment transported by the southeast stream resulted in rapid growth of the delta. Within the stream channel, fluvial processes varied between erosion and deposition. Irregular deposition in the cross-section measured could have affected the relationship between cross-sectional area and mean velocity. This may have modified the discharge estimates and therefore the stage-discharge rating curve.

The discharge of a stream is a function of its velocity, which in turn affects the competency and capacity of the stream. Furthermore, the velocity of the stream influences the momentum of the resulting current upon entering the lake. If the momentum is great, overcoming inertia of the lake water, the current and its sediment load may travel further across (or within) the lake than if momentum is low.

At the outlet of Sunwapta Lake, the Sunwapta River, a permanent gauging station has provided outflow data since 1947. Both water stage data and calculated mean daily discharges are available for the period of open water, usually from late April or mid-May to October.

Within the lake, an attempt was made to monitor

currents flowing within one to two metres of the bed. This was part of a field study on turbidity underflows carried out in Sunwapta Lake in 1974 and 1975 (Gilbert, 1975a). In the 1974 season, a correlation was found between wind velocities as measured by an anemometer, and bottom current velocities (Gilbert, 1975a). The data for 1975 have not been analysed at present, and it is not known yet whether a similar correlation existed for July and August of that year.

Drogues had been used with some success to study surface and subsurface currents in the south basin in 1974 (Gilbert, 1975a). A similar attempt in the north basin in 1975 was largely unsuccessful. Each drogue consisted of four aluminum vanes about 43 X 56cm joined at right angles. A measured length of string attached the vanes to a surface float, usually a plastic bottle or piece of styrofoam (Fig. 11). In theory, movement of a current at the depth at which the drogue is suspended pushes the drogue at the speed and in the direction of current flow. In practice, complications arise. Wind and waves affect the float, often pulling the drogue at a velocity greater than that of the current. If the wind is strong enough it may move the float and attached drogue in a direction opposite or normal to the current flow. If a deep current is transporting the drogue, the float may act as a 'drag', creating a discrepancy between the real and the apparent velocity. The smaller the float, the less its effects on drogue movement. In the

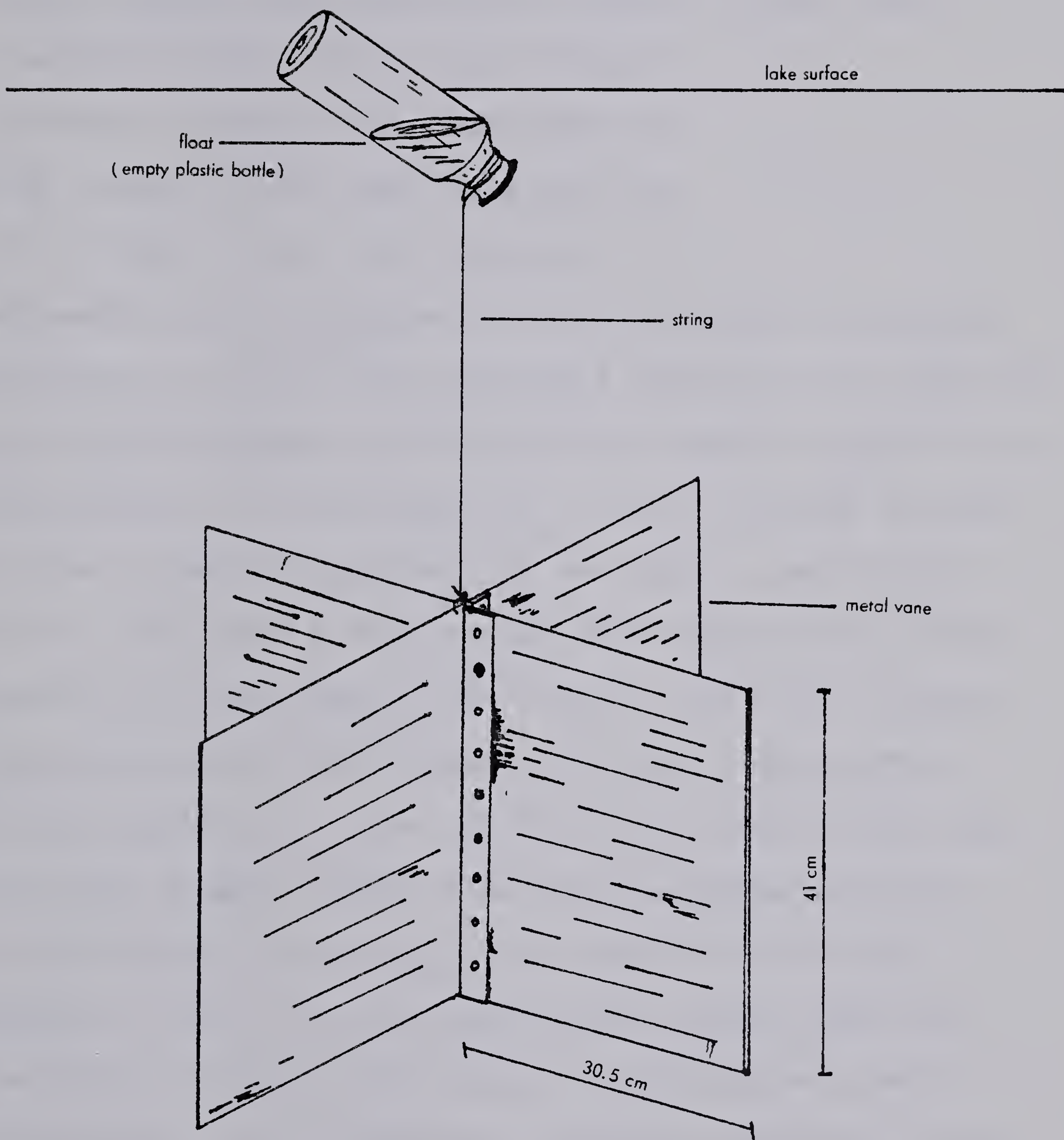


FIGURE 11
DROGUE

turbid water of Sunwapta Lake, a highly visible float was necessary; unfortunately, small brightly-coloured objects on the lake would have raised objections from the National Parks Service staff.

Four drogues were released on August 4 (Fig. 12):

1. A surface drogue in the east channel,
2. A surface drogue in the west channel,
3. A 2m drogue in the west channel, and
4. A 4m drogue in the west channel.

The movements of the drogues in the north basin confirmed observations on surface and subjacent current flow. The east channel surface drogue drifted from the narrow channel into the north basin. It was caught by a strong current flowing north from a temporary channel on the delta, and floated around the east end of the island. About one-third of the way towards the west end of the island, the float resumed its north/northeast drift towards the lake outlet. The drogue was picked up in the centre of the north basin. The west channel surface drogue floated in a north/northeast direction and was picked up in the centre of the basin northwest of Pan 2. The 2m drogue moved slowly north and then northeast towards the outlet. The 4m drogue moved north/northeast, then apparently grounded southeast of Pans 1 and 1A. The movement of the drogues agreed with wind and general lake water movement. A strong wind was blowing off the glacier, and lake water flow was from the south basin, through the west and east channels, into the north basin,

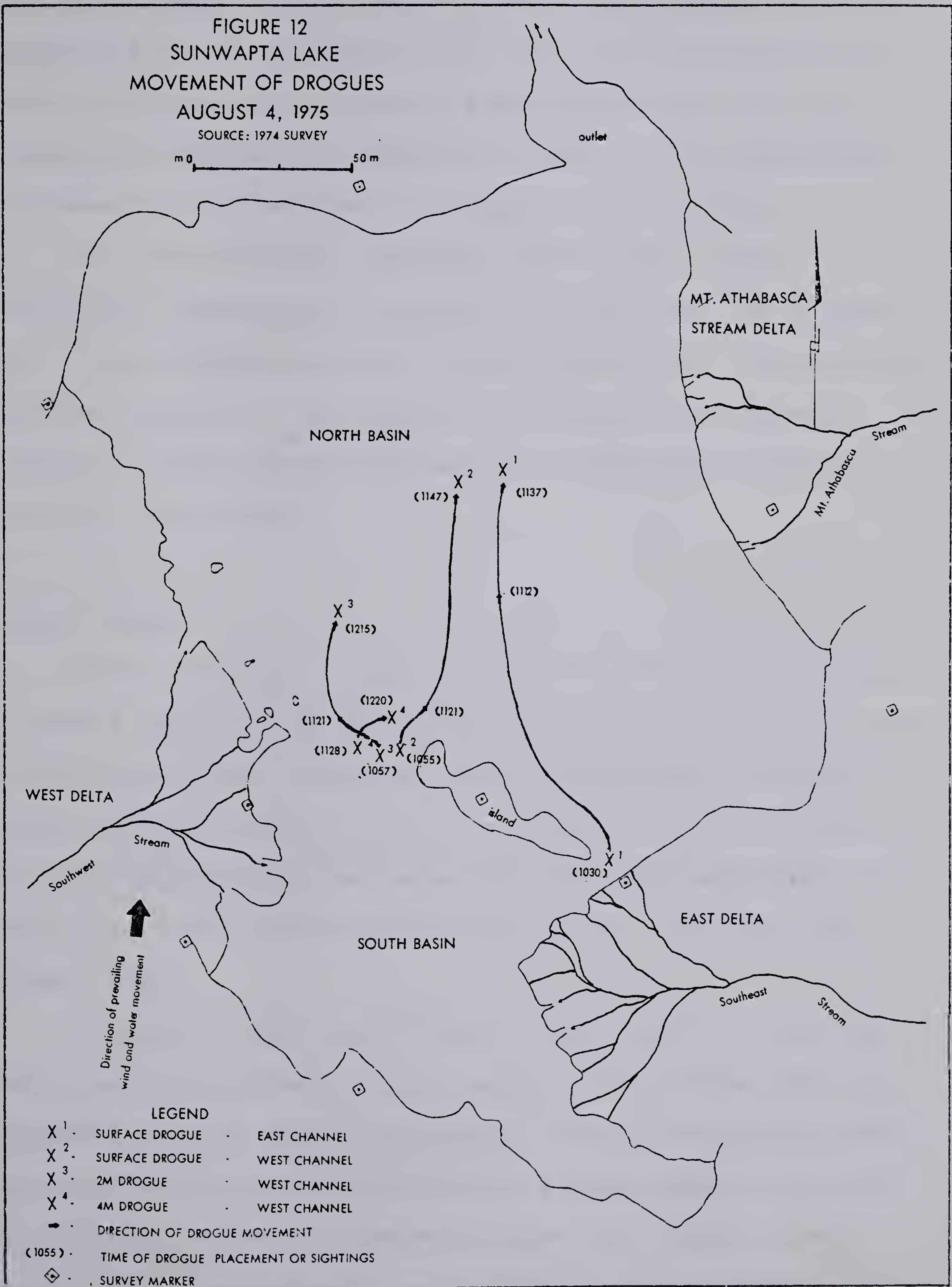


FIGURE 12
SUNWAPTA LAKE
MOVEMENT OF DROGUES
AUGUST 4, 1975
SOURCE: 1974 SURVEY
m 0
50 m
outlet
MT. ATHABASCA
STREAM DELTA
Stream
Mt. Athabasca
NORTH BASIN
(1147)
(1137)
(1112)
(1215)
(1220)
(1121)
(1121)
(1128)
(1057)
(1055)
island
(1030)
WEST DELTA
Stream
Southwest
EAST DELTA
SOUTH BASIN
Southeast
Stream
Direction of prevailing wind and wave movement
LEGEND
X 1 - SURFACE DROGUE · EAST CHANNEL
X 2 - SURFACE DROGUE · WEST CHANNEL
X 3 - 2M DROGUE · WEST CHANNEL
X 4 - 4M DROGUE · WEST CHANNEL
DIRECTION OF DROGUE MOVEMENT
(1055) - TIME OF DROGUE PLACEMENT OR SIGHTINGS
SURVEY MARKER

and towards the outlet. The exception was the temporary current flowing around the east end of the island; this was reflected in the movement of the east channel drogue. The fact that the surface drogues moved much faster than the subsurface drogues was probably a result of the decreasing influence of the wind with increasing water depth.

The lack of fixed reference points made drogue velocities impossible to measure. In addition, the drogues had to be followed by boat in order to be seen, and the boat drifted rapidly to the north. The lake was too large and turbid, and the floats too small to be followed from the island or the shore.

2.2.5 Cores

Seven cores were obtained from the bottom sediments of Sunwapta Lake on July 30 and 31. A floating platform for the gravity corer and tripod was constructed from lumber and empty oil drums (Fig. 13). In the centre of the platform an opening was left for the corer. The platform was towed to a coring site and anchored with heavy rocks (Anderson and Hess, 1969).

A gravity corer is allowed to fall freely to the lake bed. Its driving force is the weight of the corer plus any attached weights (Emery and Dietz, 1941). The gravity corer used in Sunwapta Lake consisted of a heavy metal pipe about four inches (11cm) in diameter, eight feet (about 2.4m) long, and weighing about one hundred pounds (45.4kg). Four

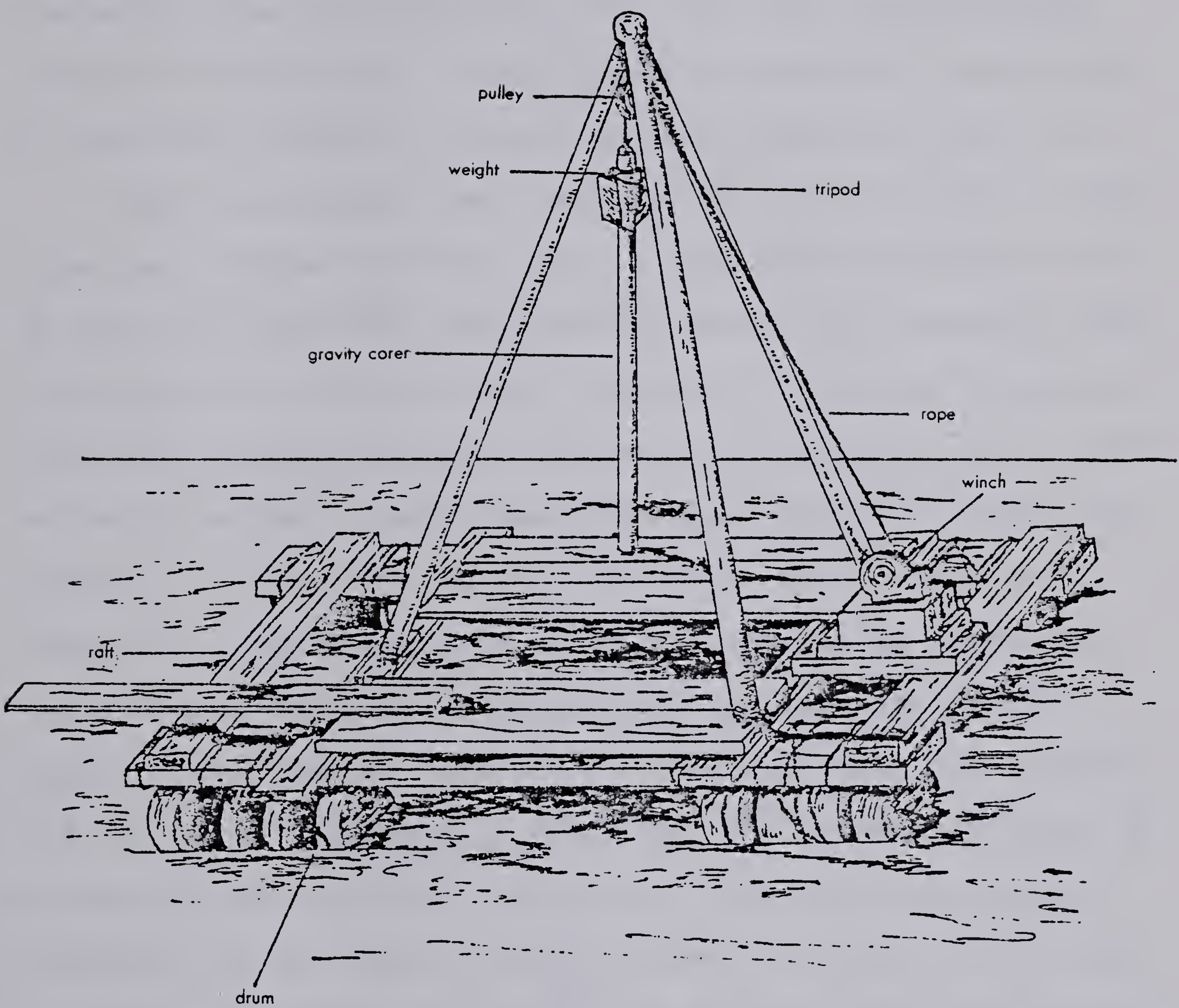


FIGURE 13
GRAVITY CORER AND RAFT

metal fins were joined to the pipe near the upper end. Before coring, a fifty-pound (22.5kg) weight was attached to the upper end of the corer above the fins, and a metal 'nose cone' screwed into the lower end to penetrate the bottom sediment. A removeable plastic core liner was fitted into the metal pipe for each core. When the core was collected and the corer raised, a core retainer inside the bottom end of the pipe closed to prevent sediment escaping (Fig. 14).

When the platform was anchored at a coring site, a core liner was slipped into the corer, the nose cone was screwed on and the corer with the attached weight was suspended from the tripod over the platform opening. A rope from the top of the corer passing through a pulley at the apex of the tripod was wound around a small hand-operated winch. The winch was attached to the platform and controlled the raising and lowering of the corer. The corer was lowered by winch over the selected site. At a certain depth, depending on the depth of the lake at that point, the winch gears were locked and the corer suspended in the lake. The strain was taken up by hand. When the corer was steady, the winch gears were released and the gravity corer allowed to drop into the lake bed sediments. The heavy corer and sediment were then raised slowly with the winch. When the top of the metal pipe was about a metre above the lake surface, the mud was cleaned off the weight and fins, and the water permitted to drain out the corer. This water was forced into the pipe as the corer was falling through the lake. When sediment was driven

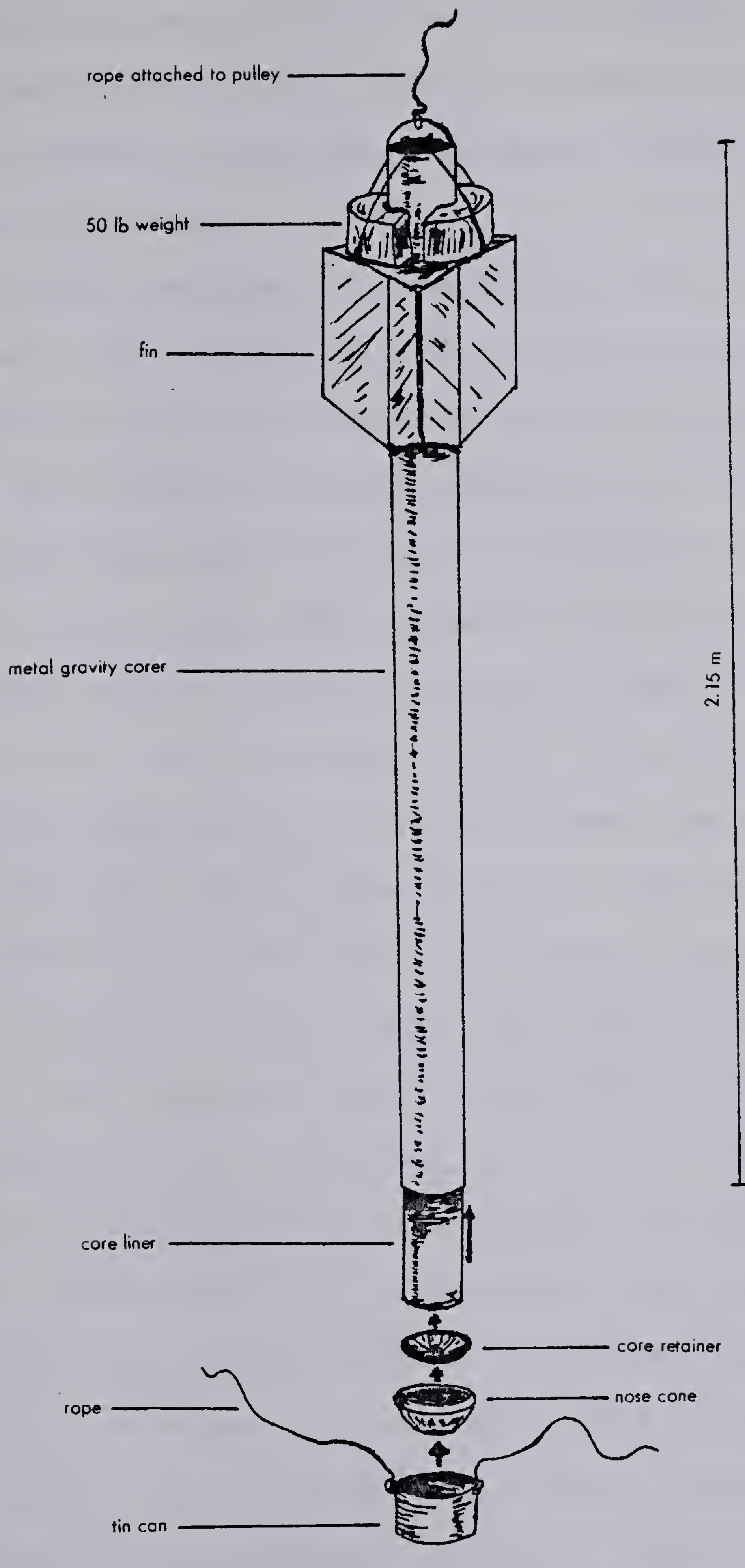


FIGURE 14
GRAVITY CORER

into the corer, some of this water was pushed out through openings at the top of the pipe, in spite of hydrostatic pressure; however, this water probably reduced the length of the cores collected.

To prevent sediment from spilling out of the corer at the surface, the bottom half of a tin can attached to strings was placed over the nose cone and bottom end of the pipe. As the corer was slowly raised to the top of the tripod, the inner plastic pipe was guided out of the metal pipe. The tin can was then replaced with a plastic lid sealing the bottom end of the plastic tube. To keep the tubes upright, each one was tied to a leg of the tripod. The tubes were transported to the field camp upright in the back of the truck and tied to the front of the trailer. The cores were allowed to dry for about two weeks. Each plastic tube and core was then split in half and left to continue drying. On August 24, the cores were transported to Edmonton for photographing and further analysis in the laboratory.

Initial difficulties in handling the corer and the unconsolidated nature of the sediment resulted in the loss of several cores. Some spillage of sediment also occurred before the bottom end of each tube could be sealed. The gravity corer has been used with better success in more consolidated lake sediments (Gilbert, 1972). Cores were taken in the general vicinity of the sediment pans, although not close enough to risk disturbing sediment in and around each pan. Three cores were collected from the south basin.

Four cores were taken from the north basin (see Fig. 6):

1. In the deepest section, south of Pan 2,
2. In the west channel, south of Pan 1,
3. In the centre of the lake, west of Pan 2, and
4. In the northeast part of the lake, opposite the outlet.

These cores should provide evidence of recent past sedimentation rates, particularly when compared with bottom sediment samples from the field season of 1975. Structures such as varves, laminations, folds and slump structures provide clues to past processes of sediment movement and deposition.

2.3 Laboratory Methodology

2.3.1 Field Laboratory

Samples collected from Sunwapta Lake were taken to the field laboratory, with the exception of those obtained at the end of the field season and brought to Edmonton. Laboratory equipment consisted of: a small electric Fisher oven for drying samples, a vacuum pump and filtering apparatus designed for Gelman 0.2 μ and Watman 50 (541) filters, a transmissivity kit, a Hach conductivity meter (after July 18), a Sartorius balance with a maximum of 160 g, a balance and scales for larger weights, containers of distilled water and assorted beakers.

The oven was kept in continuous use throughout the field season drying the sediment collected in the sediment pans. Water was used to syphon and otherwise empty the

sediment from each pan into plastic jars. At camp, the sediment was allowed to settle for several days, after which the excess water was syphoned off. The small amount of sediment lost with the relatively clear water was not considered significant. The remaining wet sediment was then emptied into several beakers and dried in the oven. Each beaker had already been weighed and numbered at the beginning of the field season. A record was kept for each sediment (or cake) pan sample consisting of:

1. The pan number or letter,
2. The date and time the sample was brought up from the lake bed, and
3. The numbers and weights of the beakers in which the sample was dried.

Time required for drying varied depending on the amount of sediment in each beaker, but averaged about twenty-four hours. A beaker remained in the oven until all visible signs of moisture had disappeared. Each beaker plus sediment was then weighed and the combined weights of the beakers and sediment for each sample were added to the above mentioned record. Smaller samples from each dry sediment (or cake) pan sample were preserved in labelled cellophane bags for later grain-size analysis. The remainder of each sample was discarded.

Knowing the area of the sediment pans and the time intervals each remained on the lake bed, it is possible to calculate rates of sedimentation for each pan. From this

information one may be able to assume sedimentation rates for each of the five representative areas shown in Figure 3: the proximal zone, the north side of the east and west channels, the deepest portion of the north basin, and the distal zone. Grain-size analysis of the smaller samples preserved should indicate distribution of grain-sizes throughout the lake.

At the beginning of the field season, all suspended sediment samples were filtered using the vacuum pump and filtering apparatus (Fig. 15). Each filter was weighed on the Sartorius balance before use. Each stream water sample was first filtered through a relatively coarse Watman 50 filter and then through the fine Gelman 0.2 μ filter. Although the filtering apparatus was designed to use both filters simultaneously, in practice it proved faster to filter first the coarse, then the fine sediment. Sand and coarse silt particles were trapped by the coarse Watman mesh; the water and finer sediment passed through into a trap flask. Distilled water was used to wash out the sample 'milk bottle' to remove any remaining particles. The Watman filter and coarse sediment were placed in a plastic petrie dish marked with a code number. The water and fine sediment from the trap flask was filtered through a Gelman filter. This filter with the trapped sediment was also placed in a marked petrie dish.

Because of the visible lack of coarse suspended sediment in the lake samples (with one or two exceptions),

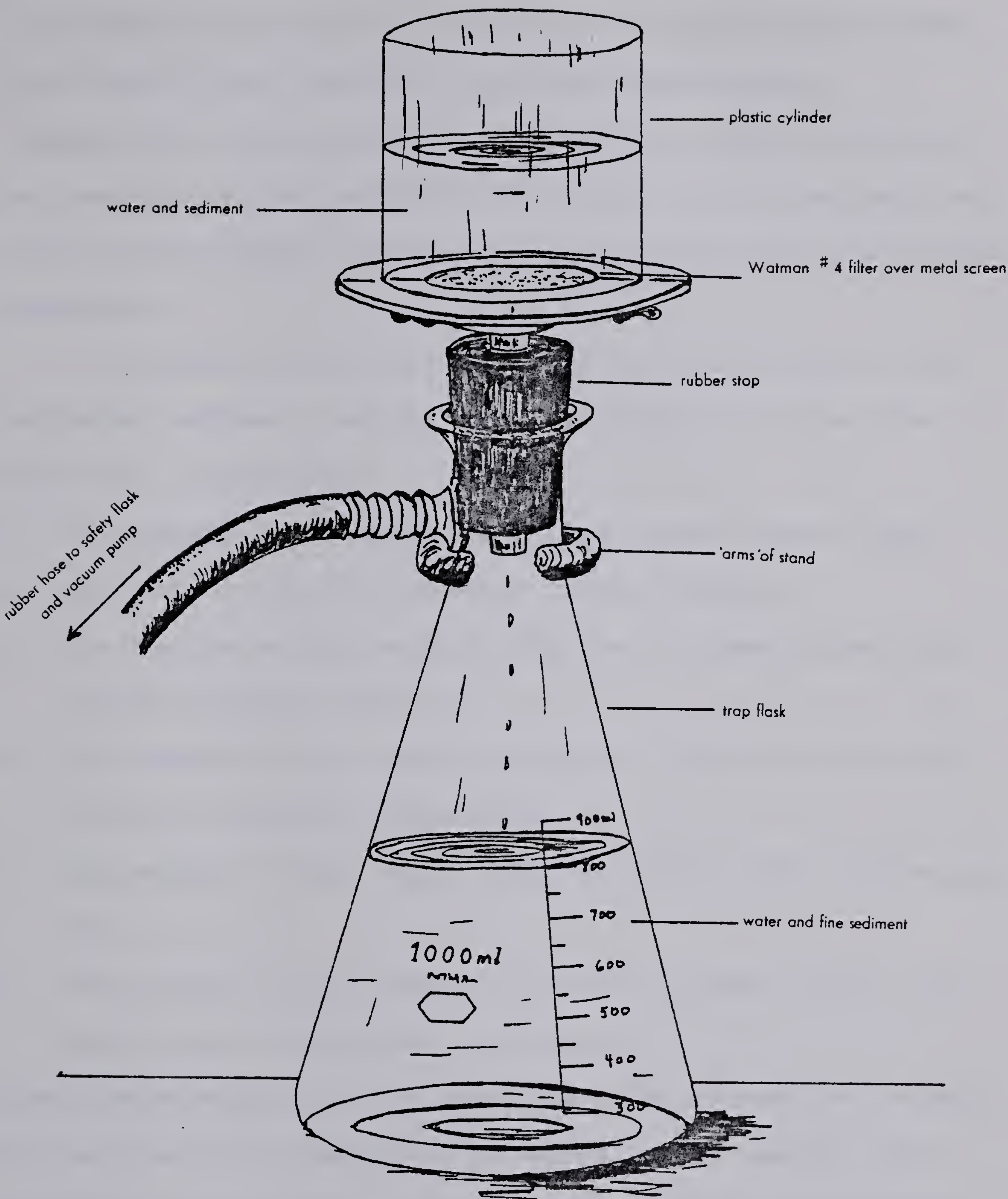


FIGURE 15
FILTERING APPARATUS WITH WATMAN FILTER

only the Gelman filter was used. The sediment caught by the fine mesh was placed in a marked petrie dish. These dishes were dried slowly on top of the oven because the temperatures inside the oven required to dry the sediment pan samples melted the plastic dishes. The dry sediment and filter were weighed on the Sartorius balance and the weights recorded.

A standard form sheet was used to record data on the suspended sediment samples from the stream and the lake. These data comprised:

1. The sample code number as marked on the petrie dish,
2. The date, time and location of each sample,
3. The weight of the Gelman filter and Watman filter (if used) for each sample,
4. The weight of the sampling bottle ('milk bottle') and contents prior to filtering,
5. The weight of the empty sampling bottle after filtering, and
6. The weight of the Gelman filter and Watman filter (if used) plus the trapped sediment.

From these weights it was possible to calculate and record, for each sample, the volume of water in the sample, the weight of the sediment, and the concentration of suspended sediment in mg/l.

A transmissivity kit drastically reduced the number of samples requiring filtering. Transmissivity is a measure of the percentage of light passing through a water sample.

Distilled water is set for a transmissivity of 100 percent; in other words, all the light from a source is assumed to pass directly through distilled water. The greater the concentration of suspended sediment in a water sample, the lower the percentage of light allowed through the sample.

Transmissivity readings were taken before, or in place of, filtering. For each reading, the needle on the gauge was set at 100 percent for a sample of distilled water. Each suspended sediment sample (in a 'milk bottle') was stirred vigorously to distribute the sediment evenly. Immediately after stirring, a smaller sample was poured into a small clear glass bottle belonging to the kit. The small bottle was shaken and placed in a compartment in the kit. The lid on the compartment was closed to prevent additional light modifying the reading, the light source in the compartment was turned on, and the transmissivity of the sample recorded from the gauge reading. The small sample was then returned to the original large sample.

Initially, both the transmissivity test and the filtering were carried out for each sample. However, when transmissivity readings were plotted against suspended sediment concentrations of lake samples as calculated from filtering results, a relationship was apparent for transmissivities between fifty and eighty percent (Fig. 16 and Appendix B). With the plotted graph, only those samples with transmissivities less than 50 percent or greater than 80 percent had to be filtered. As the majority of lake

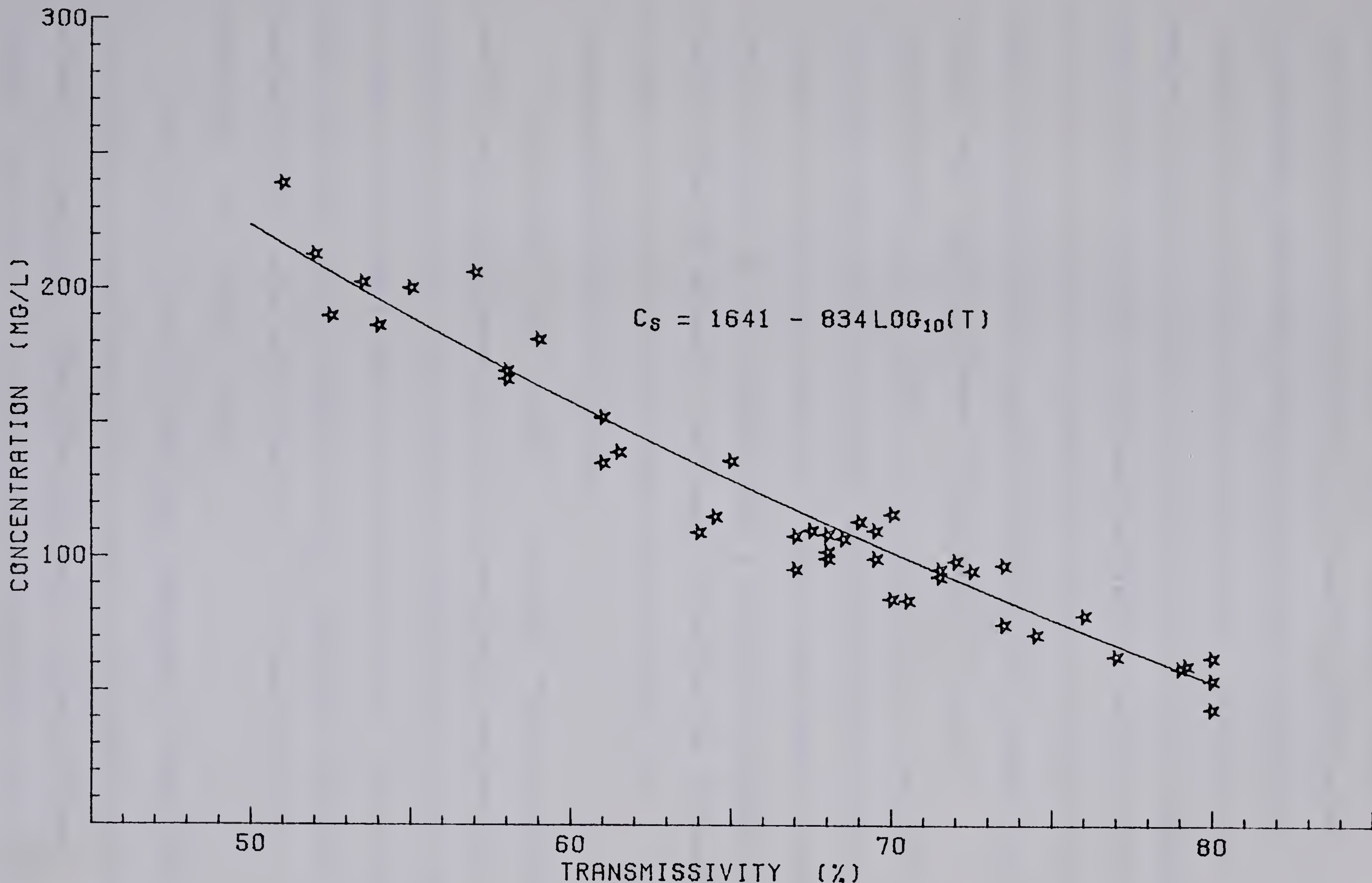


FIGURE 16. RATING CURVE FOR SUSPENDED SEDIMENT CONCENTRATION (C_S) VERSUS TRANSMISSIVITY (T).

samples fell within those limits, the graph proved a labour-and time-saving device. It was not discovered why the correlation broke down below 50 and above 80 percent transmissivity. Perhaps below 50 percent, particles are coarse enough to settle out between stirring the sediment and reading the gauge. Another possibility might be that particle-to-particle interaction in a high concentration could vary with every sample, affecting the passage of light through each sample. Above 80 percent, it may be concentrations are so small that variations in particle size and shape from sample to sample noticeably affect the passage of light and, therefore, the transmissivity reading. However, since so few samples had a measured transmissivity greater than 80 percent, one cannot discuss the existence, or lack, of correlation between concentration and transmissivity above 80 percent.

The highly turbid nature of the lake water prevented use of the transmissometer. This instrument was set for readings in the 85 - 100 percent transmissivity range. The transmissometer was used successfully in such lakes as Bow Lake and Hector Lake, Alberta, where suspended sediment concentrations were much lower than in Sunwapta Lake (Kennedy, 1975; Smith, 1975).

The limitations of space and equipment in the field laboratory prevented use of the pipette-evaporating dish method of analysing dissolved sediment concentrations. However, on July 18, a Hach conductivity meter was borrowed

from another field party. The electrical conductivity of the water in each suspended sediment sample (that is, in each 'milk bottle') was tested before the sample was filtered. Conductivity was read off the gauge as micromhos per centimetre. From a table supplied with the conductivity meter, concentration of dissolved sediment was found to equal (approximately) 0.4 times the conductivity of the sample. Concentrations were measured in mg/l. Because of the nature of the rocks in the Sunwapta Lake area, the dissolved sediment or ion concentration was assumed to consist largely of calcium carbonates. The conductivity measurement of each sample was recorded on the suspended sediment data sheet.

If dissolved sediment concentrations were high and/or varied significantly, this might have affected stream and lake water densities; this in turn would have affected the movement of the inflowing stream water and its sediment load. In Sunwapta Lake, with its consistently high suspended sediment concentrations, the effects of the dissolved sediment were relatively unimportant. Furthermore, measured conductivities were generally low, never exceeding 105 micromhos/cm in the lake, or 115 micromhos/cm in the stream. The lowest conductivity reading for the lake samples was 55 micromhos/cm. An increase in dissolved ion concentration from about 60 mg/l to about 90 mg/l increases the water density by less than 0.00003 g/cm^3 (Kennedy, 1975).

2.3.2 Laboratory

Grain-size analysis of north basin sediment pan samples was carried out, using the hydrometer method, wet sieving, and, where necessary, dry sieving; this is described in greater detail in Appendix C. Only a few samples had a significant (about 10 percent or greater) proportion of material coarser than 4 ϕ, which, on the Wentworth scale, is the division between very fine sand and coarse silt.

3. Analysis and Discussion

3.1 General

In Chapter 1, stratified flow was defined as "... fluid motions in a gravitational field which are originated or influenced by variations in density within the fluid ..." (Harleman, 1961). Variations in density between two currents, or between a current and a standing water body, are caused by differences in chemical or mineral composition, temperature differences, or differences in concentration of suspended and dissolved sediment. The density of an inflowing stream current relative to the density of the lake water determines the current's vertical position within the lake. Where the density difference is sufficient, overflow, interflow or underflow results.

3.2 Thermal Stratification

Density flow due to thermal stratification is regarded as insignificant in many small proglacial lakes for two reasons:

1. The relative similarity between stream and lake water temperatures, and
2. The overriding importance of a large and variable input of suspended sediment.

The proximity of a glacier with its accompanying cold katabatic wind is usually sufficient to keep lake water temperatures barely above freezing. This is particularly

true for small shallow lakes. Lake water temperatures remain constant both horizontally and vertically; the thermal zones (epilimnion, metalimnion and hypolimnion) common in many non-glacial lakes, cannot be established. Thermal stratification within a lake requires water temperatures above 4°C, the temperature of maximum water density, except in the hypolimnion, and a drop in temperature of 1°C for every metre of depth in the metalimnion (Antevs, 1951; Smith, 1966). The influx of cold glacial meltwater and frequent agitation by wind-induced waves create isothermal conditions within many proglacial lakes. Interflows due to temperature differences between stream and lake water cannot occur. If some of the water entering a glacial lake is non-glacial in origin, overflow or interflow due to thermal stratification could result as relatively warm stream water enters the frigid lake water. However, proglacial lakes are generally fed solely or mainly by glacial and nival meltwater streams with water temperatures almost identical to lake water temperatures. Below 4°C, smaller differences in temperature between stream and lake water are required to produce stratified flow than is the case above 4°C (Mathews, 1956; Schlichting, 1961). A change in temperature from 0°C to 4°C increases water density by 0.00132 gm/cm^3; a drop in temperature from 8°C to 4°C increases water density by 0.000124 g/cm^3 (Hodgeman, 1940). If sediment input is small and constant, only slight temperature differences are necessary to produce density flow due to thermal

stratification (Kennedy, 1975). In a proglacial lake fed by glacial meltwater streams, conditions are reversed. Temperature differences are negligible; sediment input is large and variable, corresponding to diurnal and weather-induced fluctuations in glacier melt. Within proglacial lakes, density flow, and to a large extent sediment distribution, are influenced predominantly by density variations caused by differences in sediment concentration (Kuenen, 1951).

A somewhat different situation may exist in winter if inverse thermal stratification is established. The greater density of the deep, warmer water may retard settling of fine particles from the lighter colder water layer subjacent to the lake ice. Meltwater carrying small amounts of sediment introduced after freeze-up, and which is lower in density than the deep water, may be distributed by overflow or interflow below the layer of light, relatively sediment-free lake water. A sudden heavy influx of sediment could create a situation similar to that of the melt season in which the effects of temperature are outweighed by the effects of sediment concentrations. After break-up, inverse thermal stratification may have a minor influence on the initial distribution of sediment. The relative lack of sediment at this stage could make the slight temperature difference between inflowing cold glacial water and the deep slightly warmer lake water more important than sediment concentration differences. As mentioned, such a situation

would be short-lived in a proglacial lake.

3.3 Suspended and Dissolved Sediment Concentration

Variations in dissolved sediment may generate density flow but, like thermal stratification, the effects are usually insignificant in comparison with those of suspended sediment concentration. Because the source of dissolved material is groundwater, the input of dissolved sediment into most glacial lakes is relatively constant; changes in dissolved sediment concentration within a stream or lake result from dilution during high flow. Since a lake acts as a damper on peak and low stream flows, one would expect greater fluctuation in dissolved sediment concentration at a stream sampling site than at a lake sampling site. However, the addition of groundwater to a lake could increase the dissolved sediment concentration of the lake water above that of the stream water. Given identical stream and lake water temperatures and small stable suspended sediment concentrations, small variations in dissolved sediment could be important in density flow and sediment distribution.

Suspended sediment refers to those particles kept in suspension by turbulent eddies within a water body. (For a brief discussion of suspended sediment and the fall velocity of particles in water, see Chapter 1). Although some water is displaced by the particles, the addition of suspended sediment to water increases the density of the water (or water/sediment mixture), density being "the mass per unit

volume" (Prandtl, 1952). Where sediment input is slow and constant, there will be little difference in concentration either between the lake water and the stream water or within the lake. Where sediment input is variable, discrepancies arise between the amount of material entering a lake and the amount of material settling out or being deposited in the lake over a given period of time. Because of the intimate relationship between glacier melt and proglacial lakes, the situation in many such lakes is one of large and variable sediment input during the melt season and little or no sediment input over the winter. As discussed by Kuenen (1951), such conditions produce glacial lake varves and composite varves. Little opportunity exists for lake water and stream water to equalize in terms of suspended sediment concentration. This has several important effects on sediment distribution and deposition, including:

1. The establishment of settling layers within the lake, and
2. The generation of density flows as overflow, interflow, or underflow.

Although it is generally assumed that most sediment remaining in suspension after freeze-up settles out over the winter, proglacial lake water is probably never sediment-free. As mentioned, the greater density of the warmer water near the lake bed retards the settling out of fine particles. As the particles settle, they increase the density of the lake water at lower levels, thereby slowing

the settlement of finer particles from higher levels. Amelioration of air temperatures may generate stream flow and the introduction of eroded streambed material into the lake. Slumping on delta foreset beds and the pressure of lake ice along the shore may put already deposited sediment back into suspension. These conditions are not continuous. Depending on the depth at which the sediment enters or is re-introduced into the lake, a settling layer may form in which suspended sediment concentration, and therefore density, is higher than in the surrounding water. Where slumping is involved, the settling layer may be quite thick since turbulence may carry particles in all directions. Such settling layers may affect the initial distribution and deposition of sediment when the melt season begins. After break-up, some sediment deposited in the stream channel during autumn as stream flow decreased is eroded by clean nival meltwater and carried into the lake. Nival melt, like glacier ice melt, fluctuates diurnally. Sediment input is not continuous. During the day, wind-generated turbulence and stream currents aid in keeping sediment in suspension; at night, or on overcast days, settling of suspended sediment is encouraged by:

1. The lack of turbulence generated by katabatic winds and high stream flow,
2. The low density of the relatively clean lake water,
3. The absence of particle-to-particle interaction, and
4. The formation of ice over part or all of the lake

surface during the night, reducing turbulence in the lake until late morning or early afternoon.

In most proglacial lakes, the greatest proportion of sediment enters the lake in the afternoon as stream discharge rises from relatively low morning values. In early spring, nival melt may not occur in the mornings and no sediment enter the lake until the afternoon. Because the contrast between air temperatures above the glacier and those above the lake and its surroundings is less pronounced than in summer, the katabatic winds are of shorter duration and therefore less effective in generating turbulence which keeps sediment in suspension. Little suspended sediment is added to the lake overnight. Sediment in suspension in the lake may have up to twenty-four hours to settle with little or no interruption. The shorter the period of uninterrupted settling, the greater the amount of sediment still in suspension when the next sediment influx occurs. Therefore, suspended sediment may form 'settling layers' within the lake, increasing lake water density within each layer. This in turn affects each successive addition of sediment and its distribution in the lake. For example, stream currents with low sediment concentration may be less dense than a 'layer' of lake water containing sediment from a previous influx. Overflow or interflow above the settling layer will result.

3.3.1 Overflow

Overflow occurs when a water current flows over the

surface of a body of water with a density greater than that of the current. In a proglacial lake, overflows usually result when the sediment concentration of the stream water is less than that of the lake water.

Beyond the channel mouth, the current spreads out over the lake. Current velocity decreases with distance from the mouth of the stream. If, on entering a lake, the current 'fans out' over the lake surface, the sediment deposited should reflect an equal loss of velocity at equal distances in a fan shape from the source. Both size and amount of sediment should decrease at the same rate in all directions. This is more likely where initial current velocity is low. Where current velocity is high, the 'overflow plume' may follow a preferred path across the lake in the direction of greatest momentum and lowest rate of velocity decrease. Under these circumstances, the direction in which a stream enters a lake influences the movement of the sediment or overflow plume. The preferred path of an overflow plume, and any variations in that path (due, for example, to migration of the source stream across its delta) should be reflected in sediment deposition.

Regardless of the shape of the overflow plume, coarser particles will be deposited near the mouth of the stream as competency and capacity decrease. Only the silt and clay particles are fine enough that the turbulence component of the overflow current, the upward dispersion of stream lines of flow in turbulent water, is sufficient to support the

weights of the individual particles. Fine sediment may remain in suspension indefinitely since the slightest turbulence keeps it aloft. Furthermore, mixing at the current/subjacent water interface decreases the density of the current while increasing the density of the underlying water. The fine sediment transported by overflow currents tends to be distributed throughout the lake. Overflow deposits cannot indicate time of transport and deposition unless there is a regular time sequence of overflow occurrence. In glacial lakes, such a regular pattern of sediment input takes place both diurnally and seasonally. Antevs (1931 and 1951) considered overflow a prerequisite in the formation of glacial lake varves.

3.3.2 Interflow

Interflows occur when incoming stream water is denser than the surface lake water but less dense than the lake bottom water. An interflow will descend into the lake until it reaches a level at which its density equals that of the surrounding water. The reduction of slope gradient as the current spreads out over the denser lake water, plus the resistance offered by lake water inertia, reduce current velocity and cause deposition. If stream discharge is high, the momentum will propel the interflow along a preferred path. During periods of high flow, a greater proportion of sediment will be carried a greater distance along this preferred path.

The level at which an interflow will occur is determined by the relative densities of stream and lake water, and relative densities within the lake. The presence of 'settling layers' within the lake can be a major influence on the depth of an interflow. For example, an interflow may spread out over a settling layer of higher density, which in turn may overlie water with a lower concentration of suspended sediment than either the current or the settling layer. If the settling layer were absent, the interflow with its sediment load would have descended to greater depth, the fall distance of the individual sediment particles would have been reduced, and the deposition of fine-grained material would have been proportionally higher closer to the source. The greater the fall distance of a particle, the greater the opportunity for turbulence, due to current flow, waves and possibly rain-splash, and particle-to-particle interaction to act on the particle keeping it in suspension. Only fine silt and clay is transported into the lake by interflow.

3.3.3 Underflow

Underflows, more than any other type of density flow, follow a preferred path. This is partly due to their velocity and partly to their great density relative to the overlying water. The driving force for both overflow and interflow is the original velocity of the stream current. The driving force of an underflow is a product of the weight

of its own sediment load and the velocity head, the potential energy of the current which is determined by the slope gradient. As long as the gradient is sufficiently steep, an underflow is self-renewing. Even though deposition is occurring behind the head and in the tail, the head of the underflow is eroding new sediment (Middleton, 1966a). When slope gradient decreases, velocity head is decreased. Velocity, and therefore competency and capacity, are reduced. Lateral and vertical spreading of the current takes place as the water and sediment of the underflow mix with the lake water. Sediment deposited is no longer replaced by sediment eroded by the head, the driving force provided by sediment weight is greatly reduced and the underflow dissipates. (For a comprehensive discussion on turbidity underflows and their deposits, see Kuenen, 1950 and 1951; Kuenen and Migliorini, 1951; Kuenen and Menard, 1952; Sanders, 1965; Middleton, 1966a - 1966c; and Middleton and Hampton, 1973). Underflows may flow around large obstacles, override small obstacles and climb gentle reverse slopes. High steep slopes, on the other hand, may act as a sudden check on current velocity, causing heavy deposition on the upstream side of the barrier.

Kuenen (1951) suggested that underflow activity should be most common in spring. Lake water is relatively sediment-free and the large quantities of water released by rapid snow melt cause erosion of unconsolidated streambed deposits. The suspended sediment introduced into the lake in

this manner should be sufficient to create large density differences between the inflowing stream and the lake water, resulting in turbidity underflow. There is evidence that 'flushout' of previous unconsolidated deposits does occur (Kennedy, 1975; Sugden and John, 1976). Although this phenomenon is not necessarily limited to nival meltwater, the discrepancy between the capacity of the sediment-free water and its actual sediment load from clean snow increases its effectiveness as an eroding agent, relative to sediment-laden glacial meltwater. Suspended sediment concentrations of the stream may be low in comparison with summer values, but high in comparison with lake water. It has also been proposed that underflow activity is most common in summer. The glacier ice is the major source of suspended sediment; hot weather enhances glacier melting, increasing the sediment concentration of the meltwater and generating turbidity underflows. This is most likely to occur when warm weather follows a period of cool temperatures and calm conditions. Sediment already in suspension has time to settle out, and the density difference between the lake and the stream water will be enhanced as air temperatures rise. It is possible that the occurrence of major underflow events varies from lake to lake and from year to year. Such factors as the length of the meltwater stream(s), the sediment remaining in the lake at spring break-up, winter weather conditions, conditions of snow and ice melt, spring and summer weather, and the amount

of debris in the glacier ice influence the relative densities of stream and lake water throughout the melt season.

While Antevs (1951) conceded that underflows could occur under certain conditions and contribute to the formation of proximal varves, Kuenen (1951) considered turbidity underflows a major factor in the deposition of the summer varve layer, largely because:

1. Density differences due to suspended sediment concentration between stream and lake water throughout most of the melt season would favour underflow or interflow,
2. Turbidity currents, already laden with suspended sediment would tend to deposit not erode, except in the head, and
3. Such varve features as the relative coarseness of the summer layer, laminations, and graded or multi-graded units can be produced by underflows, as shown by experiment (Kuenen, 1950; Kuenen and Migliorini, 1950; Kuenen and Menard, 1952; Middleton, 1966c).

Underflows are not constant throughout the melt season, because sediment concentration varies diurnally as well as seasonally. Furthermore, as discussed below, slumping of previous deposits may generate a turbidity current. The summer layer, if deposited largely by turbidity currents, should consist of graded and multi-graded 'units', each unit representing at least one underflow event. With increasing

distance from the proximal zone, the units are interspersed with increasing amounts of fine sediment representing settling out from suspension between events. Some of this fine sediment will also be fine silt and clay carried in the tail. This would explain in part the laminations present in the summer layers of composite varves. Since turbidity underflows would transport and deposit the largest quantity and the coarsest particles of the total sediment input, the bulk of the summer layer should consist of underflow deposits.

As the underflow moves along the lake bottom, sediment is deposited; the coarsest material in the proximal zone, increasingly finer material towards the distal zone. Within the underflow, the coarsest material is transported by the head where velocity is greatest. As the current passes over a point on the bed, the largest particles are deposited first, followed by increasingly finer material. Finally the remaining clay in the 'tail' of the current settles out from suspension. This produces a simple graded bed commonly associated with turbidity underflows (see Kuenen and Migliorini, 1950; Kuenen and Menard, 1952). If the current is travelling in pulses, an inversely graded or multi-graded deposit may result; coarse material is deposited over finer material one or more times depending on the number and strength of the pulses. Where one turbidity underflow is followed immediately by another underflow, the finest material deposited by the first flow may be eroded away,

leaving a sequence in which coarse material grades upwards into moderately fine sediment overlain by coarse material grading upwards into fine silts and clay.

Some writers (see Sanders, 1963 and 1965) have divided the sediment load of a turbidity current into: 1) the suspension load, and 2) the traction load. The former consists of those particles actually carried in turbulent suspension; when deposited, they produce such features as syndepositional deformation structures (for example, 'flame structures'), resulting from deposition during current movement and deformation by current drag. Other features include structureless fine-grained beds and fine-grained graded beds. The traction load consists of material transported by "... slumps, flowing-grain layers and moving viscous suspensions" (Sanders, 1965). Depositional features associated with movement by traction include heterogeneous structureless beds, cross-strata and coarse-grained graded and inversely graded beds. The combination of traction plus deposition from suspension produces such structures as plane parallel laminae, 'ripple-drift with deposition from above' and convoluted laminae (see Sanders, 1965, for a comprehensive discussion on structures formed by deposition from turbulent suspension and from traction).

Interflows and overflows may occur between, or during, underflow events. An underflow may originate as a slump or debris flow while density differences between the stream water and lake water produce overflow or interflow. Diurnal

and weather-induced variations in sediment input resulting in overflow and interflow are probably responsible for the light/dark couplets visible in the summer layer of many glacial lake varves. When sediment input is low and the lake water is calm, a higher proportion of fine-grained sediment settles out. After freeze-up, much of the remaining fine silt and clay is deposited. If no disturbance occurs or no new material is introduced into the lake, the slowly settling sediment forms a fine-grained structureless, or fine-grained graded, bed generally considered to be the varve winter layer.

3.3.4 Slumps

Slumping transports material downslope in bulk form. The movement of material is limited by length and angle of slope, weight and thickness of material, grain-size and percentage of clay, amount of pore pressure, and shear strength of the material (Hampton, 1972). The equation relating these variables has the form:

$$T = c + \sigma n \tan\phi + \eta\xi \qquad (3-1)$$

where c is a constant and "... T is internal shear stress, σn is internal normal stress, ϕ is the angle of internal friction, η is viscosity, and ξ is the rate of shear strain (velocity gradient)" (Middleton and Hampton, 1973). In general, a highly permeable material with low porosity on a low angle slope is not likely to move a great distance if it

does slump at all. Disturbance of material moving slowly downslope allows the expulsion of pore water, increases frictional resistance between particles and encourages re-arrangement of material into a more consolidated mass. Furthermore, a low slope gradient prevents the build-up of momentum. According to Moore's (1961) findings, "... fine-grained, rapidly deposited sediment may accumulate so fast that the processes of consolidation by reduction of pore water cannot keep pace. This results in excess pore water pressures within the buried sediment and does not allow the normal increase in shear strength with depth of burial." Under conditions of slow deposition, the presence of clay-sized grains increases the cohesion of a deposit. By filling in pore spaces and increasing the surface area of particle contact, clay augments frictional resistance in unsorted sedimentary deposits. With rapid deposition, the reverse occurs. A high percentage weight of clay in the deposits increases the density of interstitial water and lowers the permeability, thereby retarding expulsion of pore water and increasing instability. Only 10 percent of the sediment deposited need be clay in order to reduce expulsion of pore water and sustain sediment movement downslope (Hampton, 1972). Many proglacial lakes experience rapid deposition during peak flow periods.

The fluctuating input of suspended sediment associated with glacial lakes may create a situation in which:

1. 'Layers' of unconsolidated sediment with a high porosity

and low percentage of fine-grained material, deposited rapidly during peak flow events, alternate with

2. 'Layers' of less permeable material with a higher percentage of clay, deposited during succeeding stages of low flow.

An overlying clay bed would greatly hinder expulsion of pore water from underlying rapidly deposited beds of coarse silt and sand, while increasing pore water pressure because of the additional sediment weight. Shear strength is decreased by increased pore pressure and consequent reduction of internal frictional resistance. Shear stress is high because of the sediment weight, the steep delta slope and the stress exerted by the passage of water currents.

Slumps may be generated by rising seepage pressure as lake levels fall (Andresen and Bjerrum, 1967). Groundwater could provide the necessary seepage pressure since groundwater flow would tend to be more constant than stream flow and resulting lake levels. Slumping may also be generated by liquifaction of rapidly deposited fine sand. Experiments have shown that "... the structure of a submerged loose sand will collapse with a slight vibration or shock [increasing pore water pressure]. During a brief period, the sand will behave as a liquid ..." (Andresen and Bjerrum, 1967). Beds of loose, rapidly-deposited fine sand are likely to be present on the foreset beds of proglacial lake deltas after peak flow events. The triggering mechanism may be ice or large stones carried down by the stream, the

action of lake ice along the shore, the movement of animals on the delta near the water's edge, or the occurrence of slumping on other parts of the delta.

A phenomenon often associated with subaqueous slumps is the generation of a turbidity underflow (Morgenstern, 1967; Hampton, 1972; Gilbert, 1975b). From observation and experiment, Hampton (1972) proposed that an increase in water content could transform a slump into a debris flow in which movement "... occurs along innumerable shear planes within the body of the material." Further dilution and decrease in density of a high-velocity subaqueous flow may occur, either through the breaking of interfacial waves or by turbulent mixing between the flow and the overlying water. A turbidity underflow may result. With a high water content, comparatively little internal frictional resistance, and high momentum sustained by a steep slope gradient, an underflow can travel a great distance, relative to slump movement, into the lake before dissipating. Because of its slower velocity, the slump material may override and even disturb the deposits of the preceding underflow. Thus, one may find coarse-grained graded deposits underlying the folds, faults, sediment fragments and similar structures associated with slumped material. While distribution of sediment by slumping tends to be localized, slump-generated underflows may transport sediment as far as the distal shore. Regardless of whether turbidity underflow does or does not occur, particles already settling in the lake will

be disturbed and new material put in suspension. The movement of displaced water and any turbulence generated by the flow will aid in keeping the sediment in suspension. In addition, the circulation patterns within a lake will have a longer period of time in which to exert their influence on the particles; a higher proportion of sediment, including, perhaps, coarse silt and fine sand, may be carried further into the lake than would be the case if the sediment were allowed to settle out undisturbed.

3.4 Sunwapta Lake

Sunwapta Lake, in 1975, consisted of a south basin and a north basin 9m and 11m deep respectively, separated by an island and its east and west underwater extensions (see Figure 3). Of the channels connecting the basins, the west channel with a depth of about 6.5m was the wider and deeper. The east channel was only 2 - 3m deep and was noticeably reduced in area by the growth of the east delta in 1975.

3.4.1 Recent History

Sunwapta Lake has been in existence since the mid-1930's (Kucera, 1972). Sedimentation studies in the lake over the years have been complicated by several factors:

1. The increasing area of the lake as the Athabasca Glacier retreated,
2. The predominance of different influent streams in different years, and

3. The large input of suspended sediment into the lake.

When Mathews (1964b) carried out his sediment transport study of the Sunwapta River in 1957, the south basin was about half its present size. A calving ice front formed the south boundary of the lake. Major stream flow was directly into the north basin; from the southeast, meltwater from the Athabasca Glacier, and from the east, the Mt. Athabasca stream. While the southeast stream was the major source of water and sediment, the Mt. Athabasca stream was apparently more active than in later years. Sediment pans placed in the confluence zone of water from both streams showed the highest rate of sedimentation in the north basin - 0.5 $g/cm^2/day$ (Mathews, 1964b). Because of the position of the streams relative to the north and south basins, this was probably the highest rate in the lake. West and north of this zone, rates of sedimentation declined with distance; in the northwest corner, deposition was estimated as 0.001 $g/cm^2/day$.

In 1974, readings taken with a Raytheon high and low frequency survey sounding system located the greatest thickness of sediment in the deep, flat-floored section of the large basin (Gilbert, 1975a). An area of sediment deposits over 8m in thickness, lying north of the island and the east channel, probably reflects:

1. Depressions in the original lake bed which served as 'sediment traps'. The effect of sedimentation in Sunwapta Lake, as in many lakes, has been to create a

flatter lake floor than that formed by the bedrock and non-lacustrine deposits.

2. The location of the major source stream at the time of Mathews' work on Sunwapta River (1957). The southeast stream with its suspended sediment load flowed directly into the north basin. As the velocity of surface and subsurface flows decreased with expansion of the current and the effect of lake water inertia, current capacity and competency were reduced. Deposition occurred. Underflows, generated by slumping on the steep (over 9.5°) east ridge or by dense, sediment-laden stream water,deposited the largest portion of their sediment load just beyond the break-in-slope, that is, at a depth of about 11m.
3. With retreat of the glacier, the movement of sediment via the east and west channels into the broad expanse of the north basin. Since the general movement of water was north or northeast towards the outlet, much of the suspended sediment carried by overflows or shallow interflows was distributed over the deepest section of the basin. (This was observed, for example, in late June, 1975). Some loss of velocity occurred when the currents flowed north beyond the narrow confines of the channels, particularly the east channel. Velocity reduction was not as great north of the wider west channel, and sediment was carried further to the northeast rather than being deposited immediately beyond

the channel. Slumping prevented accumlation of deposits on the steep slopes of the ridge.

A second area of thick deposits extending west of the Mt. Athabasca stream may relate to the former significance of that stream. In 1975, the Mt. Athabasca stream was relatively inactive except during periods of high air temperature.

By 1974, the glacier margin had retreated several metres south of the lake. The dominant stream, from the moraine-covered ice southwest of the lake, discharged into the south basin (Gilbert, 1975a). Although several channels entered north of the island, the main stream flow was southeast and a counterclockwise circulation pattern resulted in the south basin (Gilbert, 1975a). Flow northwards towards the outlet was split by the island and restricted by the channels.

No sediment studies were carried out in the north basin in 1974. The effect of sediment input from the southwest stream on this basin must be surmised from the configuration of the lake and possibly from core features.

3.4.2 The Southeast Stream

3.4.2.1 Hydrology

In 1975, the situation changed. The southeast stream, which the summer before had been a relatively insignificant braided stream, became the major source of water and sediment for the lake. The southwest stream and the

Mt. Athabasca stream apparently contributed little except in periods of hot weather.

Suspended sediment concentrations in the southeast stream in 1974 were estimated at 20 - 100 mg/l at high flow (Gilbert, 1975a); in 1975, concentrations as high as 3150 mg/l were recorded. From a tunnel on the east side of the glacier, the stream skirted the ice front as a single channel before branching out over the east delta. At the end of June, the stream was confined to one channel and flowed southwest into the south basin. New channels were established and old ones relocated as discharge increased. The position and relative importance of several stream channels varied frequently during the field season.

Because the southeast stream was a glacial meltwater stream, it was expected that discharge, and to some extent, the sediment load, would reflect conditions of glacier melt. Glacier melt in turn would reflect weather conditions in the area of Athabasca Glacier. Although it was not possible to measure actual temperatures and precipitation at Sunwapta Lake, some general weather information is available for the summer of 1975. Daily observations were kept for July and August of temperature, rainfall, snowfall, wind and cloud cover. In addition, data on daily maximum and minimum temperatures and precipitation for May through October were obtained from the Jasper weather station (Fig. 17 and 18). Variations in weather noted at Sunwapta Lake, such as high temperatures or periods of heavy rain, resemble weather

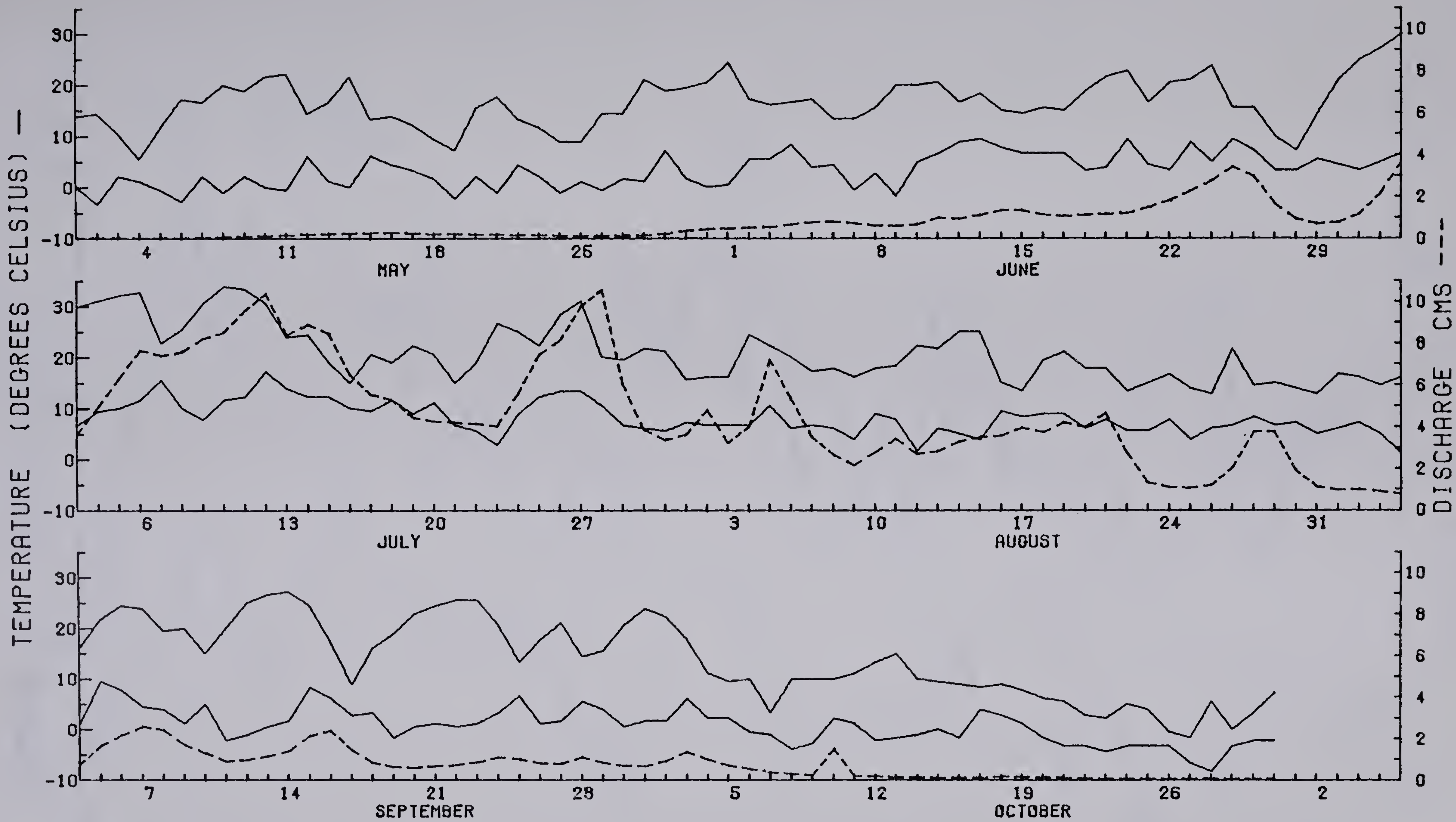


FIGURE 17. MEAN DAILY DISCHARGE FOR THE SUNWAPTA RIVER AND THE MAXIMUM AND MINIMUM DAILY TEMPERATURES AT THE JASPER WEATHER STATION, MAY 1 TO OCTOBER 31, 1975.

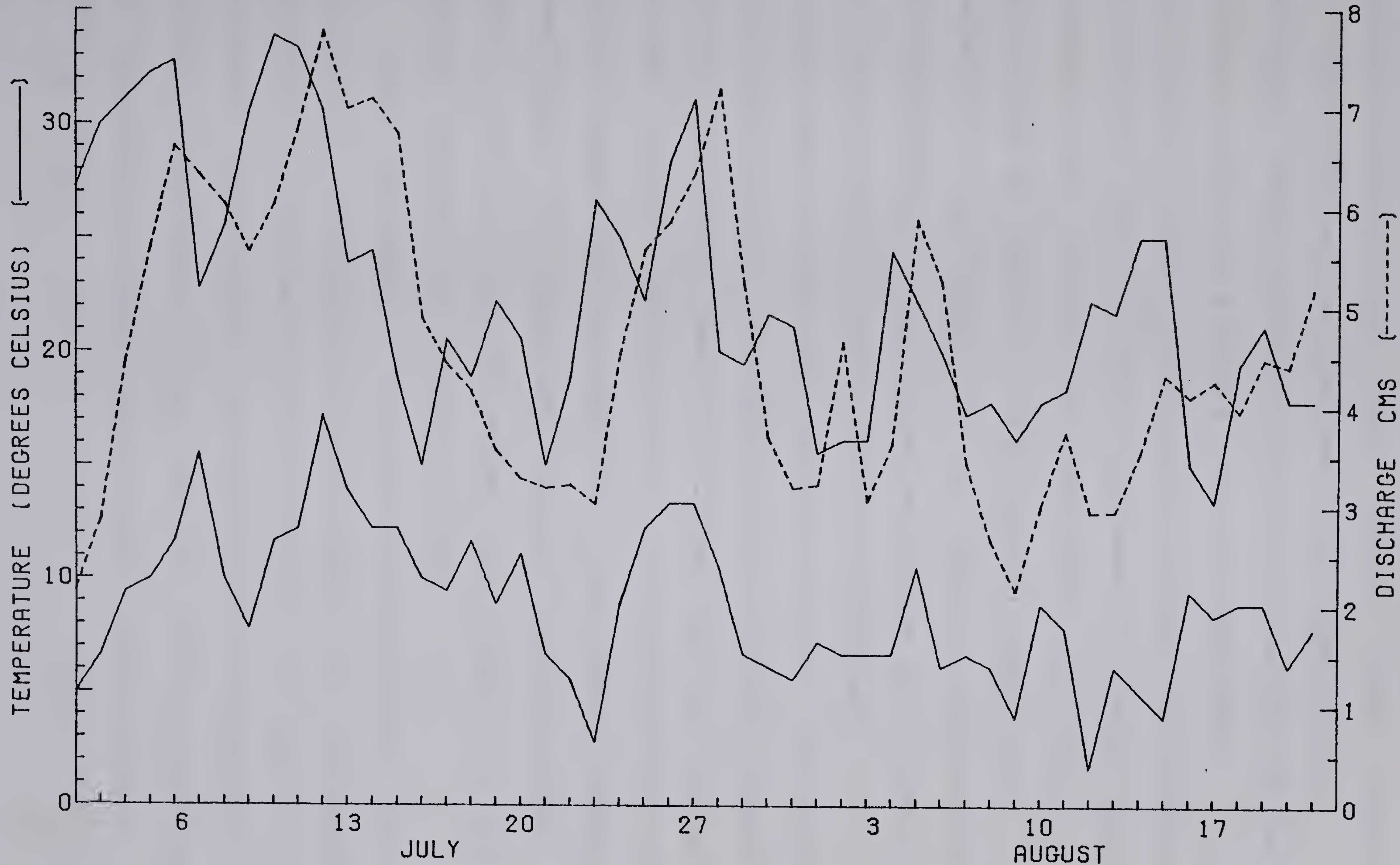


FIGURE 18. MEAN DAILY DISCHARGE FOR THE SOUTH-EAST STREAM AND THE MAXIMUM AND MINIMUM TEMPERATURES AT THE JASPER WEATHER STATION, JULY 2 TO AUGUST 22, 1975.

conditions registered at Jasper (Mathews, 1964a). Comparison of temperature records from the weather station with discharge records for both the east delta stream and the Sunwapta River show a fairly close correspondence, particularly between high discharge readings and periods of warm weather (Fig. 17 and 18). Because the distance from the glacier margin to the lake is very small, any increase in melt caused by rising air temperatures is immediately reflected in the discharge of the stream (as estimated from a stage-discharge rating curve, see Figure 10). A time lag of one to two days is often evident between peak temperatures at Jasper and peak flow events in the stream; since this is an area of eastward-moving weather systems, this lag is probably due to the distance and location of the Columbia Icefield 100km southeast of Jasper and almost 700m higher. Temperatures are moderated by the higher altitude. Nevertheless, the Jasper meteorological records provide a good indication of general weather conditions in the area of Sunwapta Pass and the Athabasca Glacier.

Within the immediate vicinity of Sunwapta Lake, the proximity of the Athabasca Glacier results in a periglacial mesoclimate. Short-term weather conditions are unstable and subject to rapid changes. Any increase in air temperature is usually accompanied by strong katabatic winds sweeping down off the glacier. Adverse weather conditions at Sunwapta Lake affected the field work carried out in the summer of 1975.

3.4.2.2 Sediment Input

Mean daily discharge in the southeast stream corresponded to changes in air temperature, both diurnally and over long periods of time (Fig. 18). Suspended sediment concentration in the southeast stream also increased during periods of warm weather. However, an analysis of the data indicates a low correlation between actual discharge and the corresponding concentration measurements (Fig. 19A and 20A); these differences may be explained by:

1. Mistakes in the sampling and filtering procedures. However, since both techniques were relatively simple, any errors would not have resulted in such wide discrepancies in values.
2. The proportion of material transported by the stream as bedload. This proportion increases as stream velocity increases. Since only suspended sediment was sampled, it is likely that a major portion of the stream's sediment load was ignored, particularly during periods of high flow, because of the lack of sampling techniques. This study was concerned with processes operating within the lake and therefore with sediment carried in suspension (except in relation to underflow activity). Plotting discharge against suspended sediment concentration, the greatest point scatter on the graph corresponds with high discharge values (Fig. 20A).
3. The erosion of previous unconsolidated deposits with greater discharge, increasing the suspended sediment

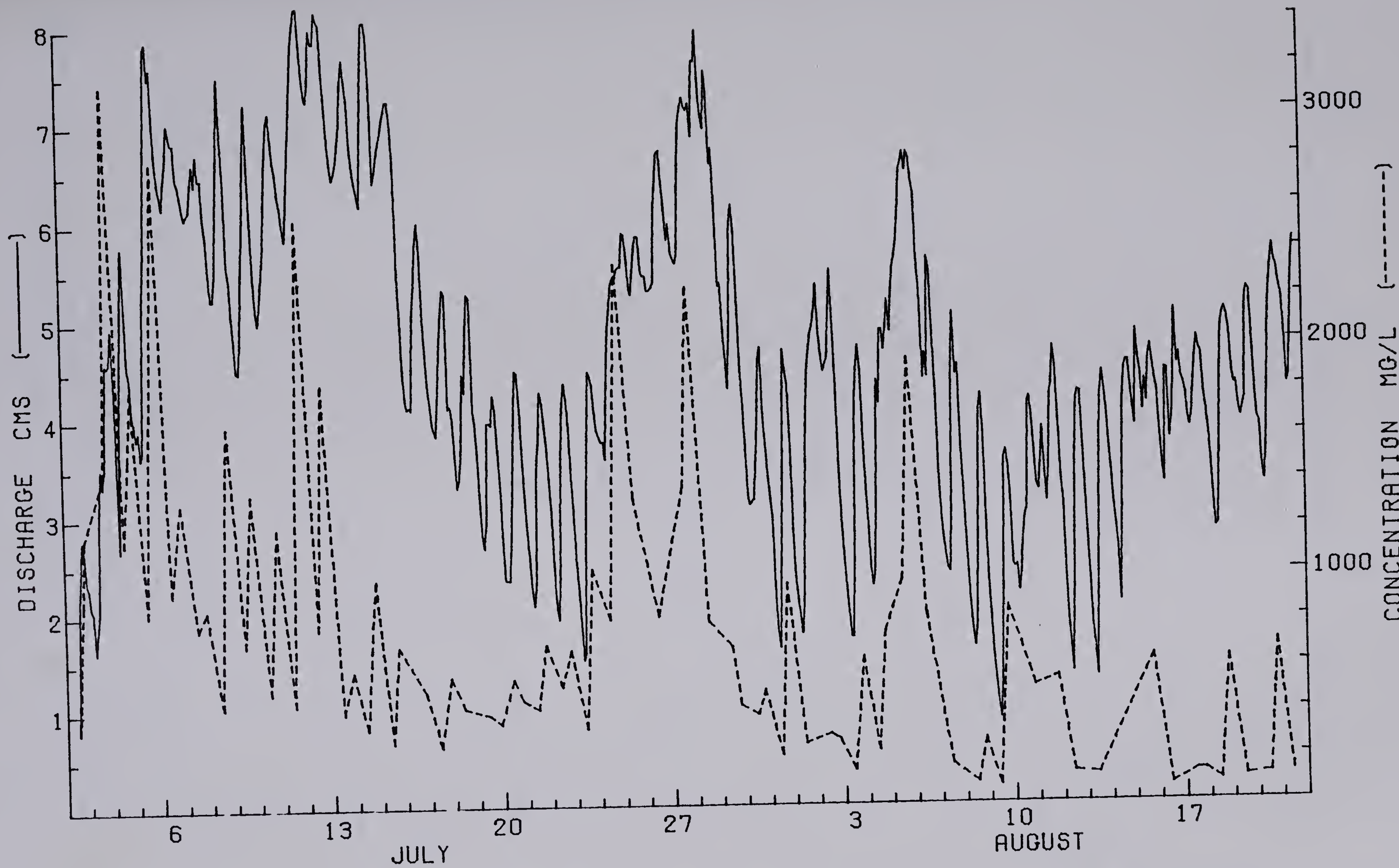


FIGURE 19A. DISCHARGE AND CONCENTRATION IN THE SOUTHEAST STREAM, JULY 2 TO AUGUST 22, 1975.

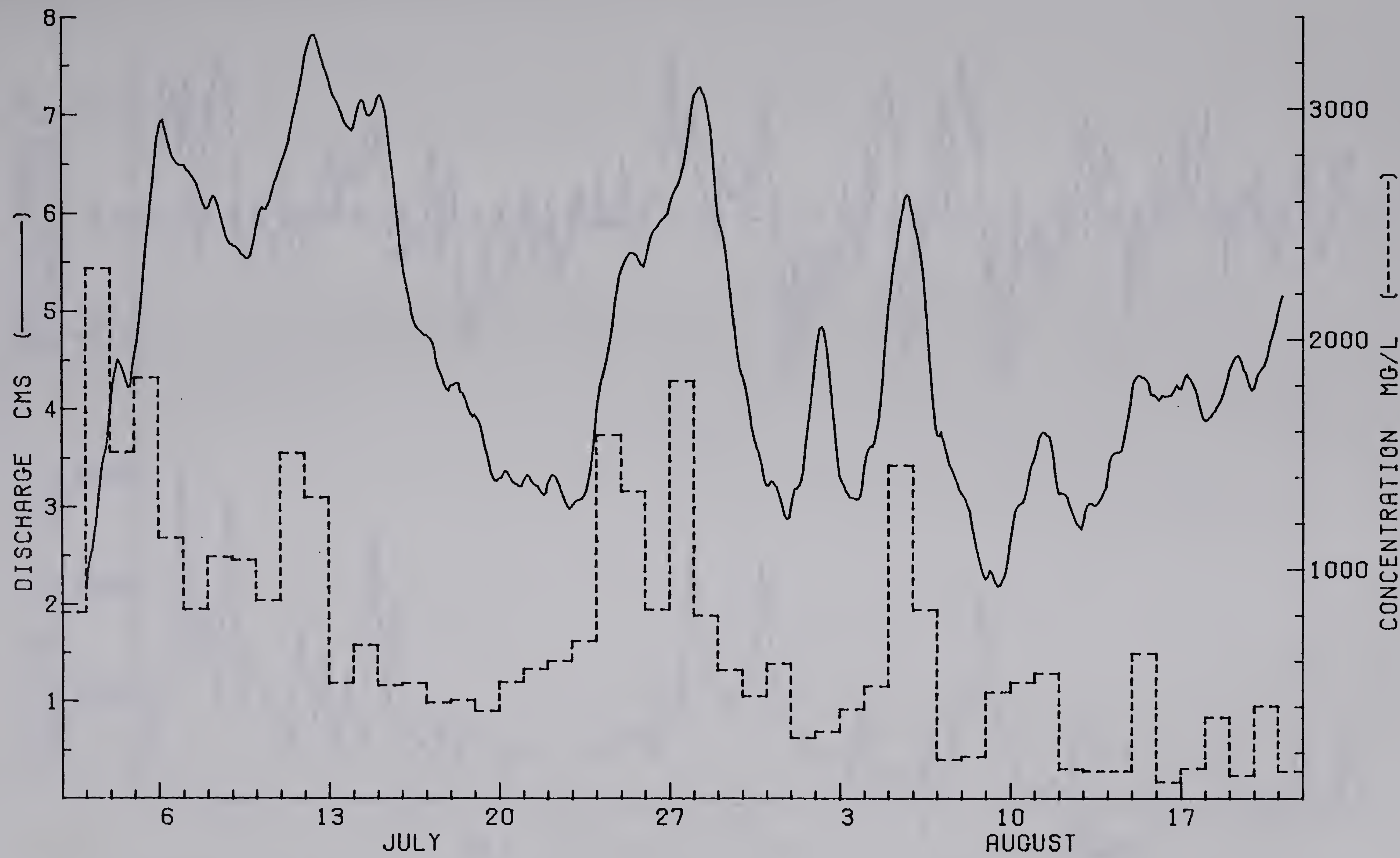


FIGURE 19B. AVERAGE DISCHARGE AND MEAN DAILY CONCENTRATION IN THE SOUTHEAST STREAM, JULY 2 TO AUGUST 22, 1975.

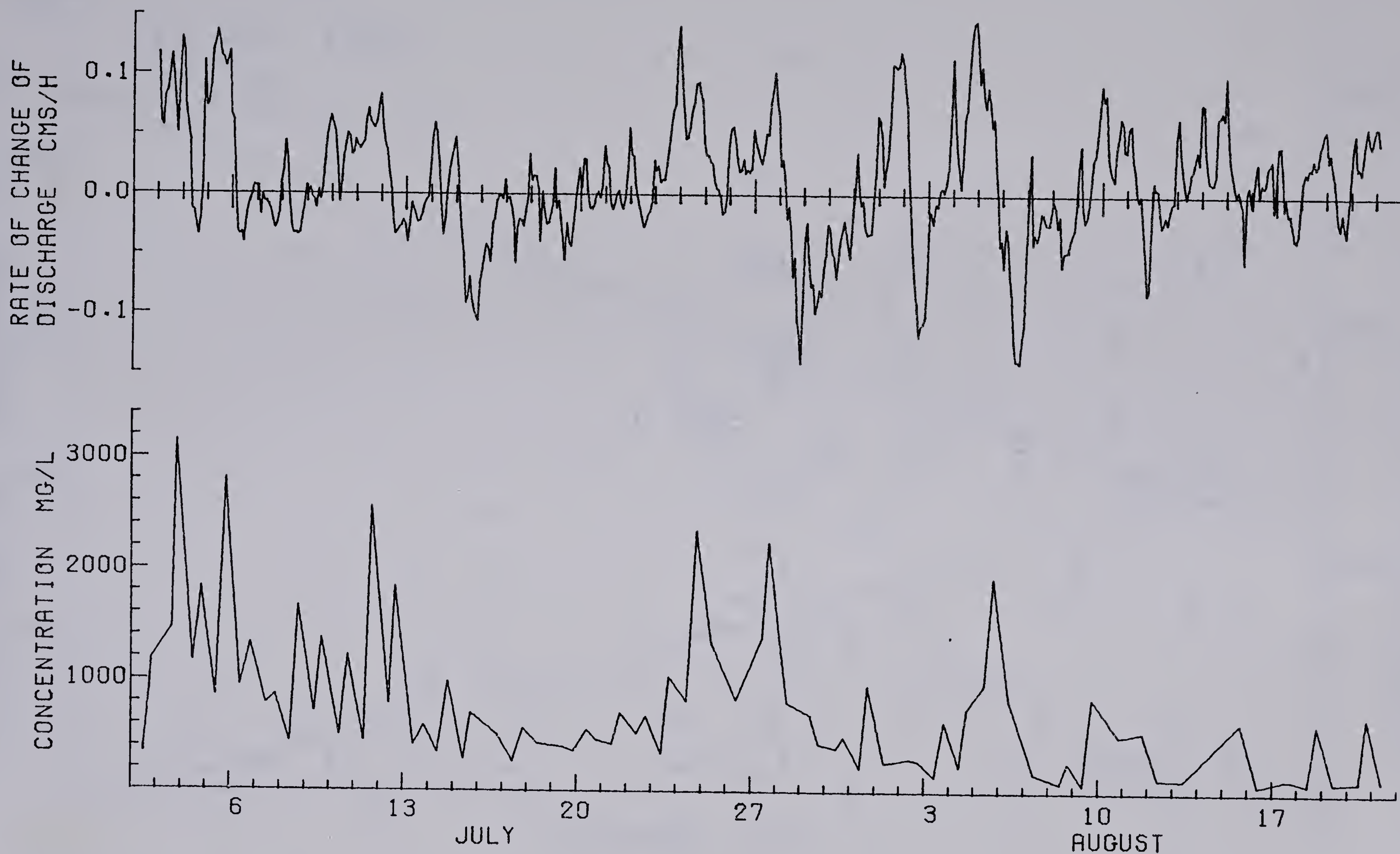


FIGURE 19C. CONCENTRATION AND RATE OF CHANGE OF AVERAGE DISCHARGE IN THE SOUTH-EAST STREAM, JULY 2 TO AUGUST 22, 1975.

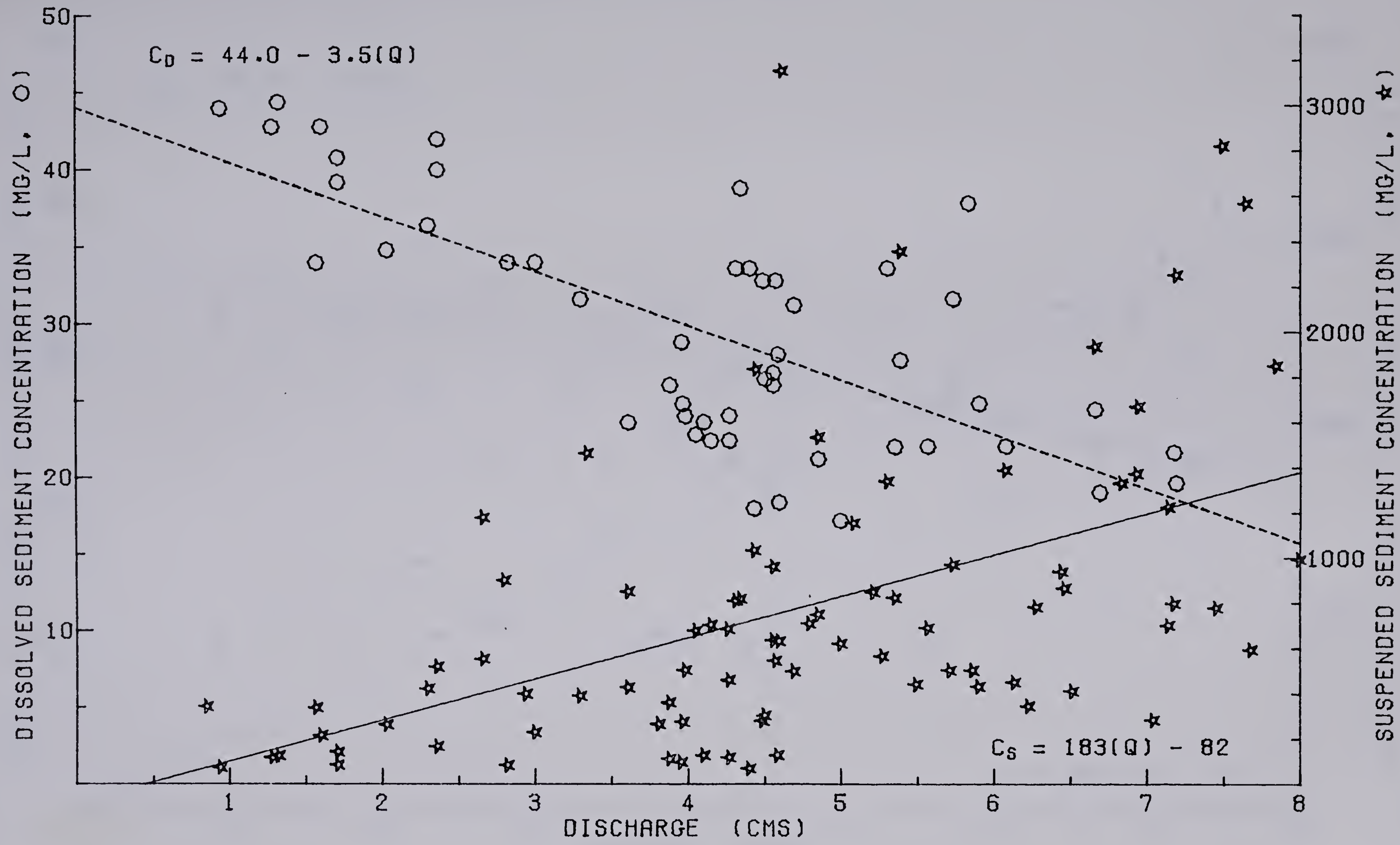


FIGURE 20A. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

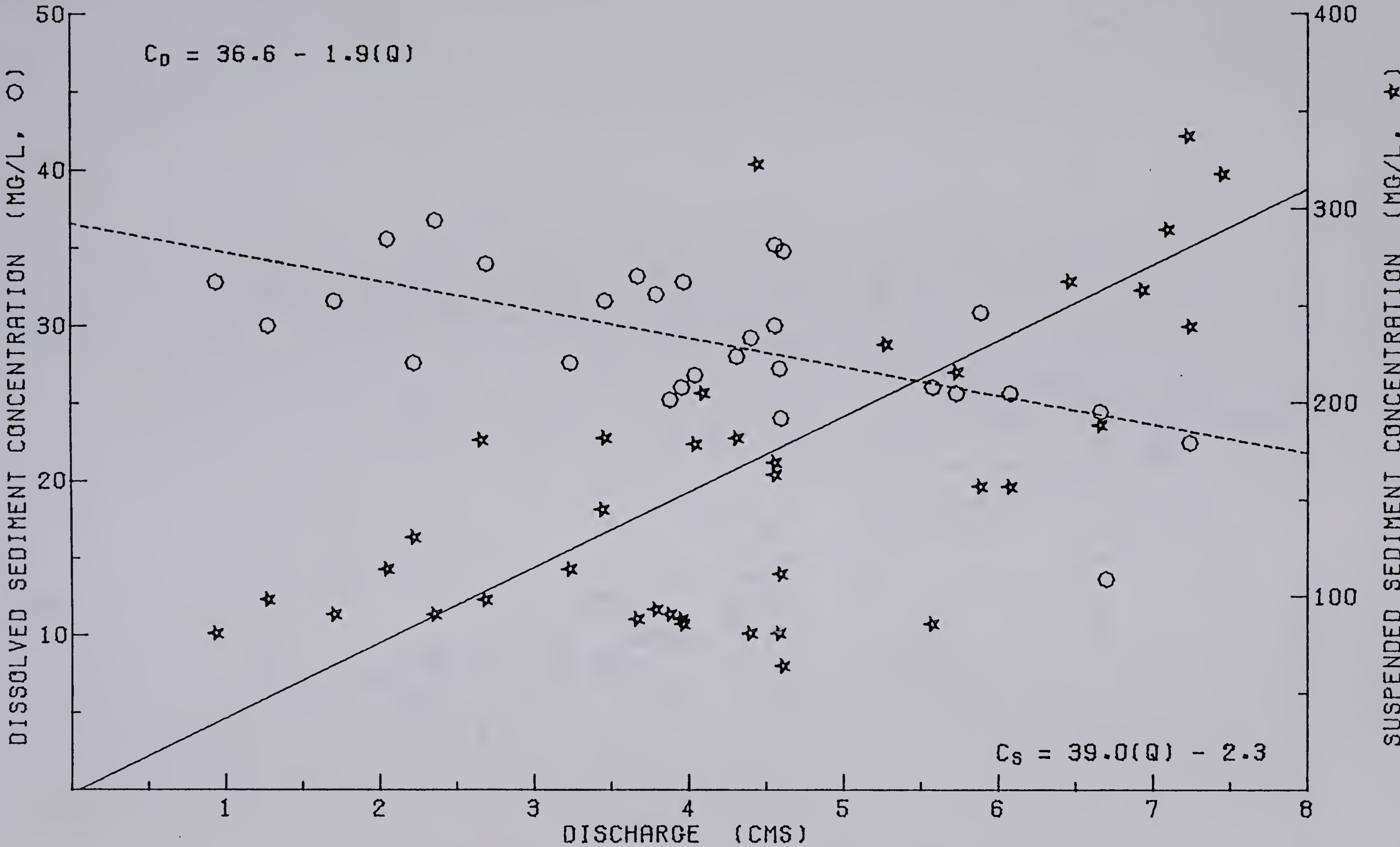


FIGURE 20B. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) AT PAN B SITE VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

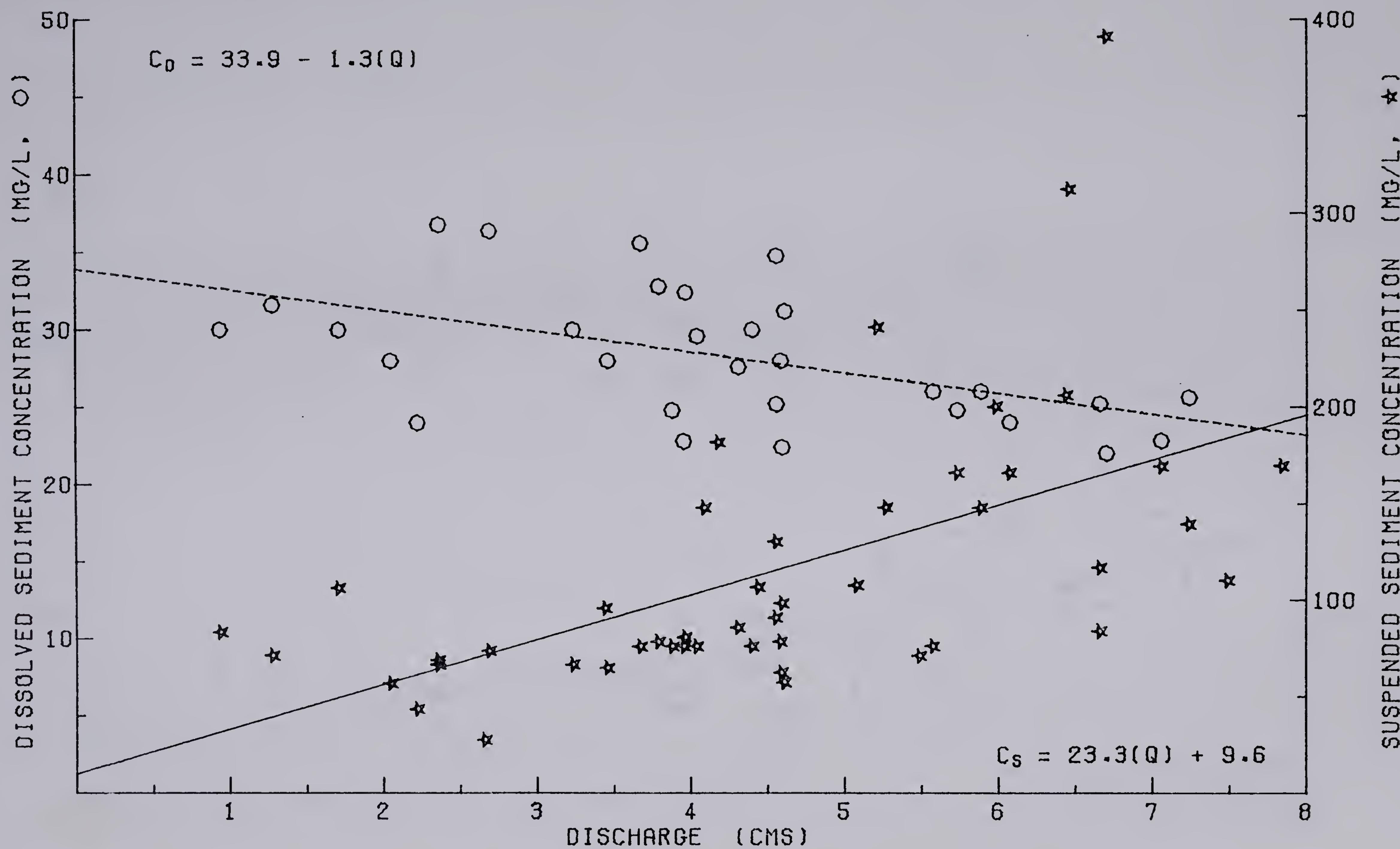


FIGURE 20C. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) AT PAN 1 SITE VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

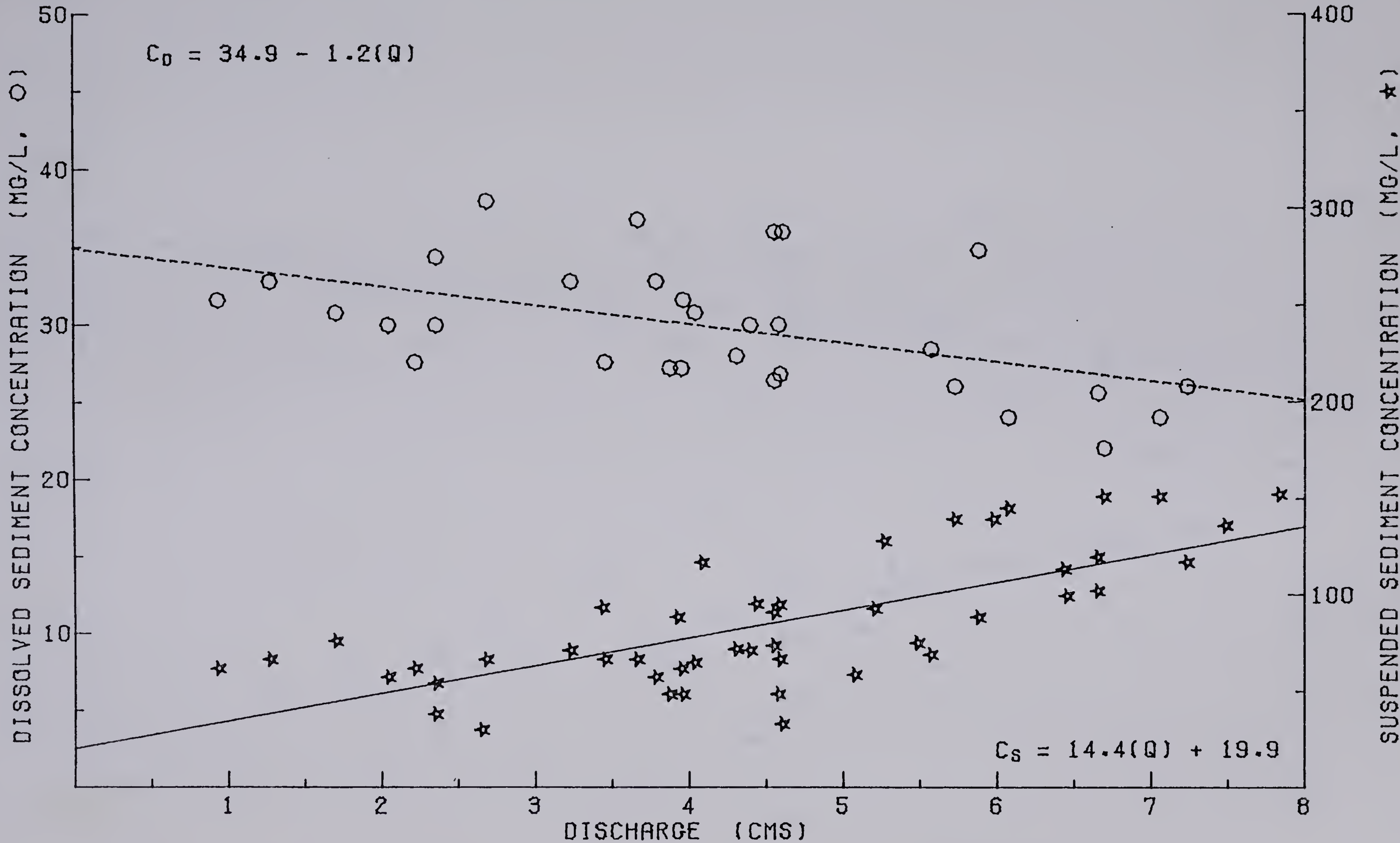


FIGURE 20D. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) AT PAN 2 SITE VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

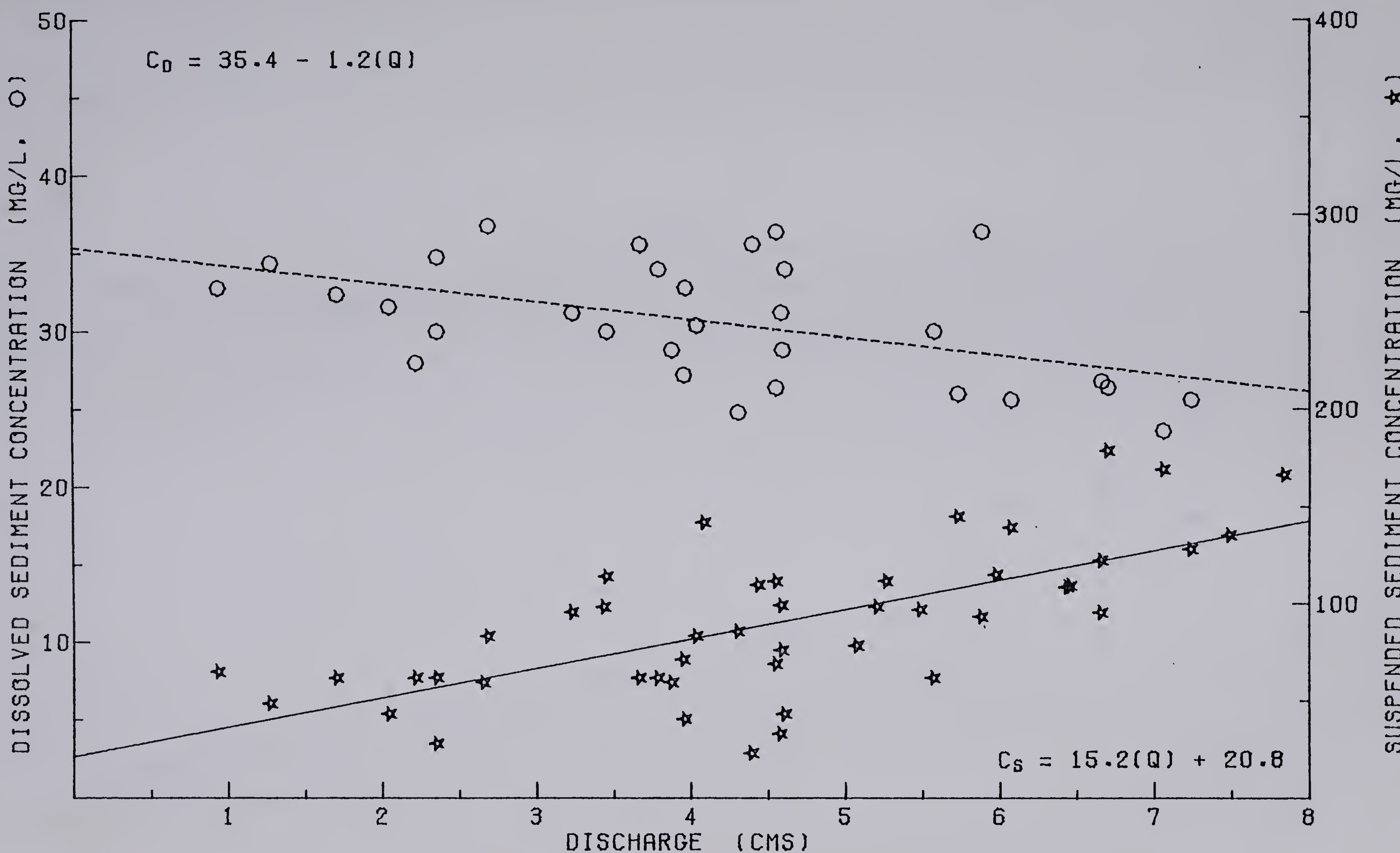


FIGURE 20E. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) AT PAN 3 SITE VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

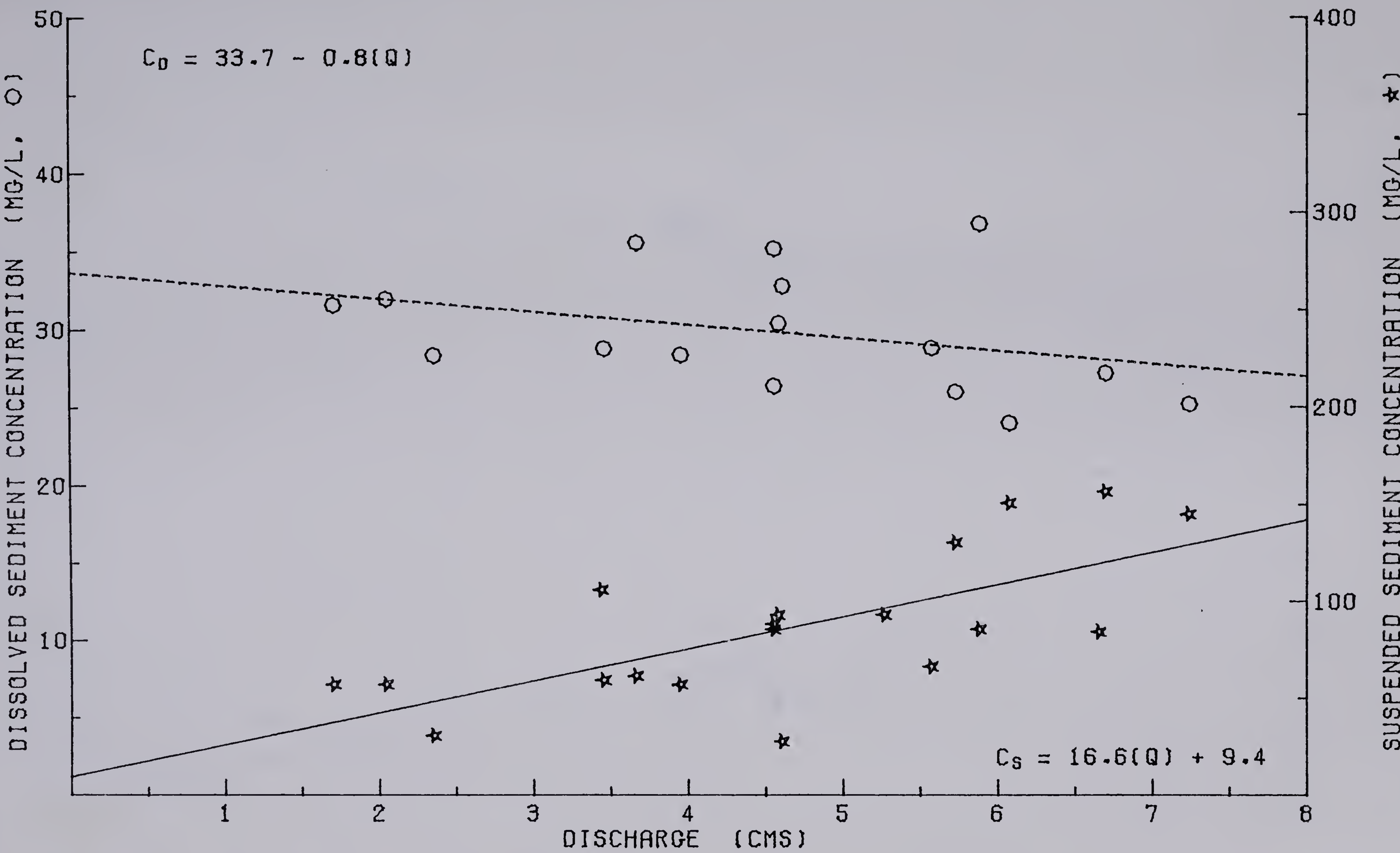


FIGURE 20F. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) AT PAN 4 SITE VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

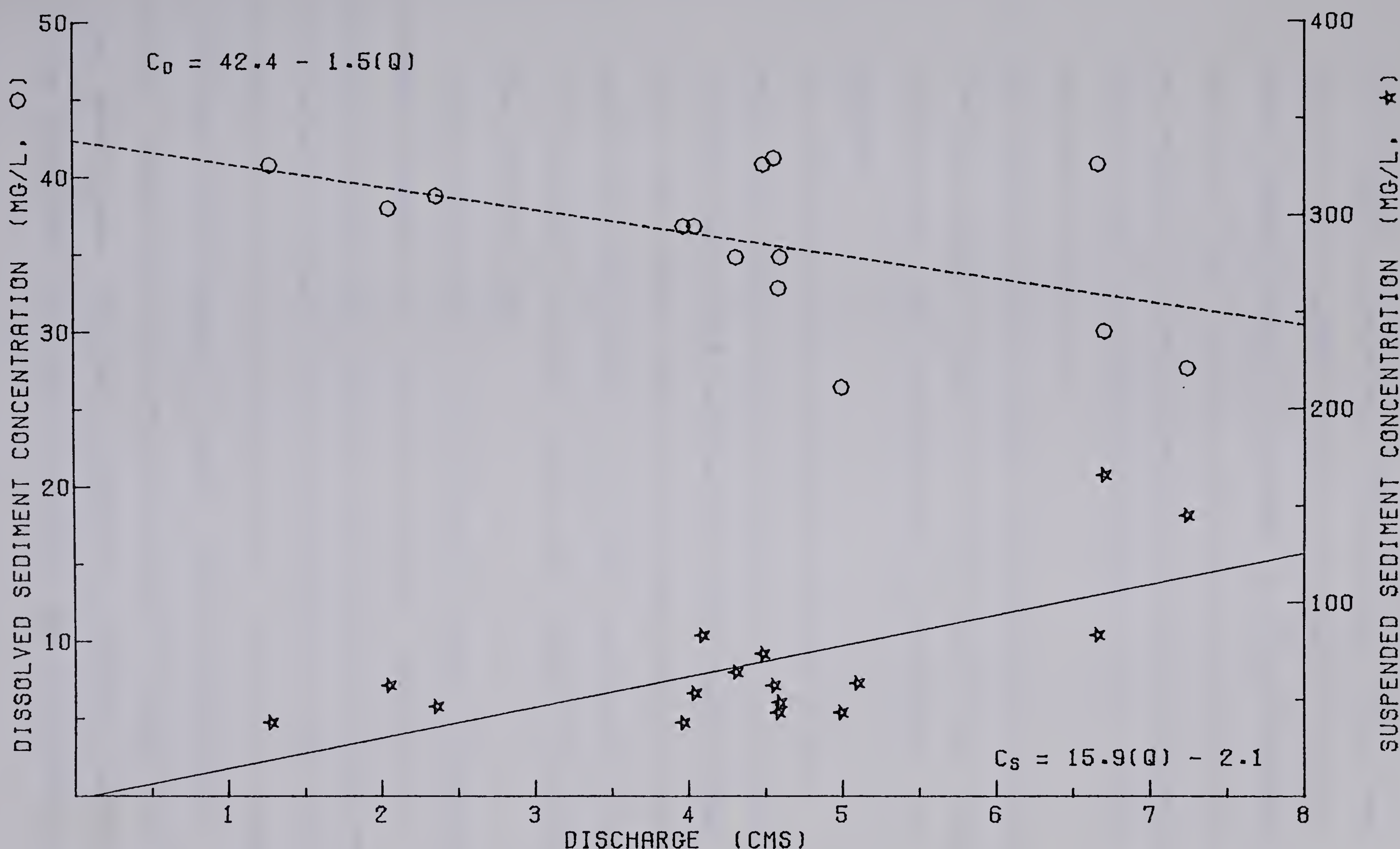


FIGURE 20G. PLOT OF CONCENTRATIONS OF SUSPENDED SEDIMENT (C_S) AND DISSOLVED SEDIMENT (C_D) AT OUTLET VERSUS DISCHARGE FOR THE SOUTH-EAST STREAM.

concentration (Morisawa, 1968; Kennedy, 1975). When material was removed, concentration fell. Discharge often remained high or continued to rise. Therefore, periods of high discharge were associated with both high and moderate-to-low concentration values, although the initial result of increased discharge was an influx of suspended sediment.

4. The amount of debris in the ice supplying the meltwater. Glacial material tends to be concentrated along shear planes rather than scattered equally throughout the glacier.
5. The addition, to the southeast stream, of water previously stored within the glacier and from which the sediment had largely settled out. This could either dilute the concentration of suspended sediment already present in the stream, or it could increase the capacity of the stream, causing erosion and thereby increasing the sediment load.

From Figure 19A, it is difficult to see a relationship between discharge and suspended sediment concentration because of large daily changes. These diurnal effects can be eliminated by comparing the average discharge (over 24-hour periods) with mean daily concentration, as shown in Figure 19B. This figure appears to show a better correlation between changes in discharge and changes in concentration than does Figure 19A. The calculated correlation coefficient is low (R^2=0.20), but this is probably due to the fact that

the relationship is non-linear. The concentration at any particular time is a function of both previous discharge and previous concentrations. From Figure 19B, it would appear that the exceptional peaks in concentration correspond to rapid increases in discharge. Figure 19C compares rates of change of average discharge with concentration measurements; the peak values of concentration occur at times when discharge is rapidly increasing. The overall trend of varying concentration and varying discharge is a result of fluctuations in sediment supply from glacier ablation. The exceptional high peaks are probably the result of erosion of unconsolidated deposits due to rapid increases in average discharge and, therefore, in stream capacity.

A negative correlation existed between stream discharge and dissolved sediment concentration (Fig. 20A). Dissolved sediment concentrations, which did not fluctuate as widely as did suspended sediment concentrations, generally ranged between 20 and 45 mg/l. Since changes in stream discharge were the result of glacial melt and not of variations in groundwater flow, the relatively low and consistent values (in comparison with suspended sediment values) were not unexpected. Daily and long-term variations in dissolved sediment concentration were caused by dilution with increased discharge. Higher concentrations corresponded with periods of low flow - in the morning or during cool weather.

Because the southeast stream was the major source of water and sediment, any change in discharge and sediment

concentration of this stream was reflected in the lake. This was apparent from fluctuations in lake level and from samples of suspended and dissolved sediment (Fig. 21A and 21B, pocket part). Generally, concentrations from the Pan B and Pan 1 sites showed the closest correspondence to concentrations and discharge in the southeast stream both in amount and in range of variation. Discrepancies between high concentrations in the stream and low concentrations at Pans 2 and 4 (or vice versa) probably resulted from the time lag between a sediment influx into the lake and that sediment reaching the north basin. Periods of warm weather and high discharge were marked by high sediment concentrations for all sampling sites.

3.4.3 Processes of Sediment Distribution in Sunwapta Lake

Thermal stratification was not a significant factor in sediment distribution in Sunwapta Lake. The lake was only 0.3km in length, several metres from the glacier front, and frequently agitated by katabatic winds and high-velocity currents. In 1974, current meter and anemometer records showed lake bottom water to be strongly influenced by wind (Gilbert, 1975a). A deep layer of relatively stable temperature could not become established in summer. Neither thermal nor inverse thermal stratification occurred during the melt season. During the field season of 1975, lake water temperatures were considered uniform throughout, and, like stream water temperatures, just above 0°C.

It is unlikely that dissolved sediment was responsible for stratified flow in Sunwapta Lake during the summer of 1975. No doubt variations in groundwater flow occurred, but any effects of the contribution of dissolved sediment by groundwater to the southeast stream and the lake were completely outweighed by the large input of suspended sediment. Only outlet samples showed possible results of additional groundwater flow. Dissolved sediment concentrations sampled in the outlet remained higher all summer than at pan sites within the lake (Fig. 21B). Clear groundwater was observed entering the lake along the Mt. Athabasca stream delta. The addition of this groundwater from the calcareous bedrock and till deposits surrounding the lake could account for the increased dissolved sediment concentrations in the Sunwapta River, despite the fact that mean daily discharge in the outlet exceeded that of the east delta stream (Fig. 17 and 18).

Pan sites B,1,2,3, and 4, and the outlet all showed a negative correlation between southeast stream discharge and dissolved sediment concentration (Fig. 20B - 20G). The range of concentration values was small, from 22 mg/l to 38 mg/l. Lower values occurred in the afternoon and during periods of warm weather and high discharge (Fig. 21B). Dissolved sediment concentration in the east delta stream showed greater variation throughout the summer than did concentrations within the lake. However, there was enough similarity in the dissolved sediment concentration of lake

and stream water, and a uniformity of concentration from lake surface to bed as shown by Van Dorn bottle samples (Fig. 22B), that the effects of dissolved sediment on density stratification were considered negligible.

A. Overflow and Interflow

Density stratification caused by variations in suspended sediment was probably the single most important factor in the distribution and deposition of sediment in Sunwapta Lake. Throughout the summer of 1975, suspended sediment input was both large and variable. The estimated suspended sediment load of the southeast stream in July and August ranged from less than 40 metric tons on August 19 to over 1,435 metric tons on July 27 (Fig. 23). Suspended sediment concentrations show diurnal fluctuations increasing in range with increased discharge and consequent greater sediment input (Fig. 19A). For the first week in July, stream concentrations sampled varied as much as 1000 mg/l between morning and afternoon values. An increase in concentration of 1000 mg/l adds 0.00062 g/cm³ to the density of the water (that is, the stream water/sediment mixture) if the water density is 1.0 g/cm³. In contrast, the lower discharge of mid-August corresponded with only slight differences between morning and afternoon concentrations.

It is probable that all three types of density flow - overflow, interflow and underflow - operated in Sunwapta Lake. Given the location of the lake with respect to the

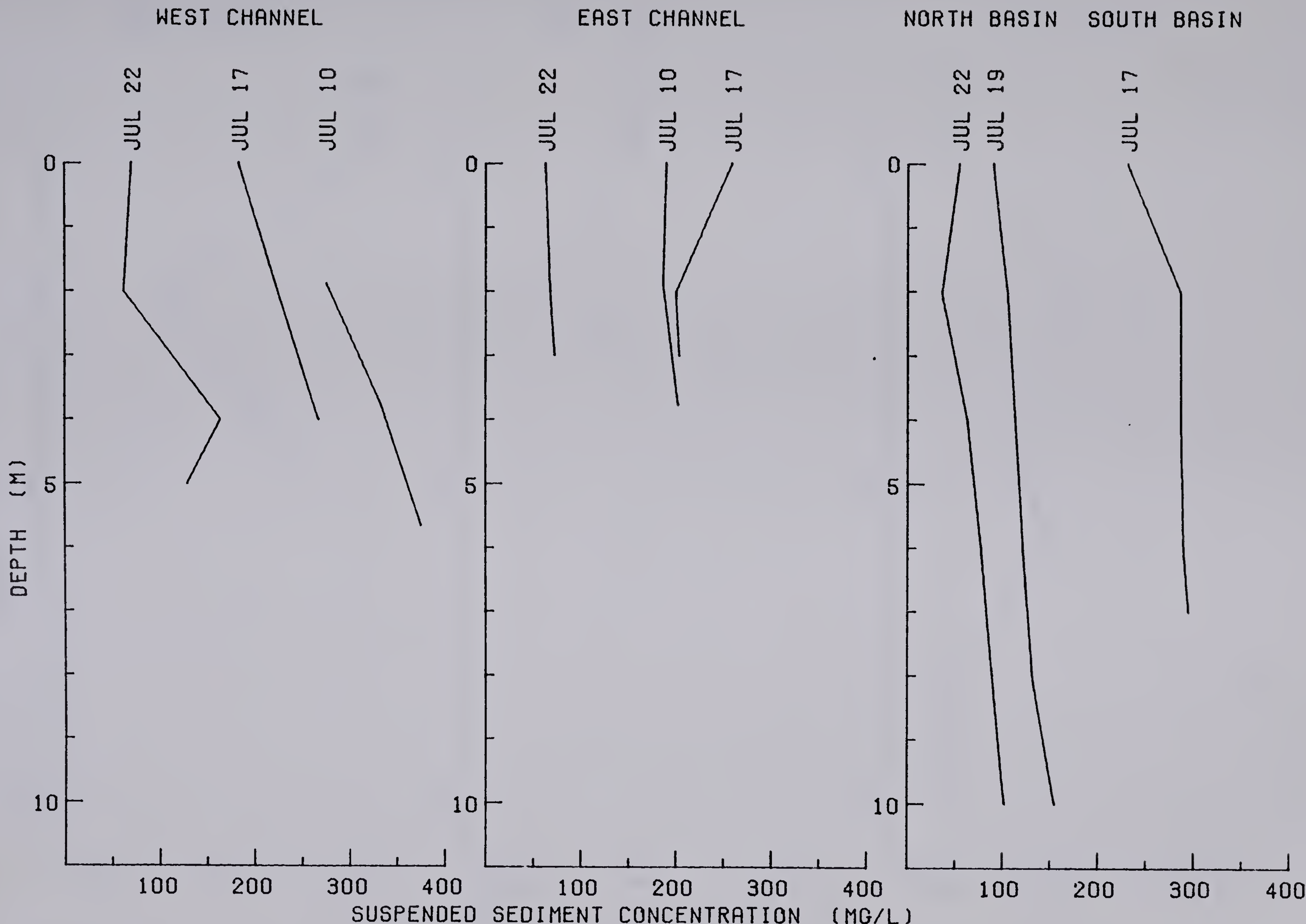


FIGURE 22A. SUSPENDED SEDIMENT CONCENTRATIONS IN SUNWAPTA LAKE FROM VAN DORN BOTTLE SAMPLES, JULY, 1975.

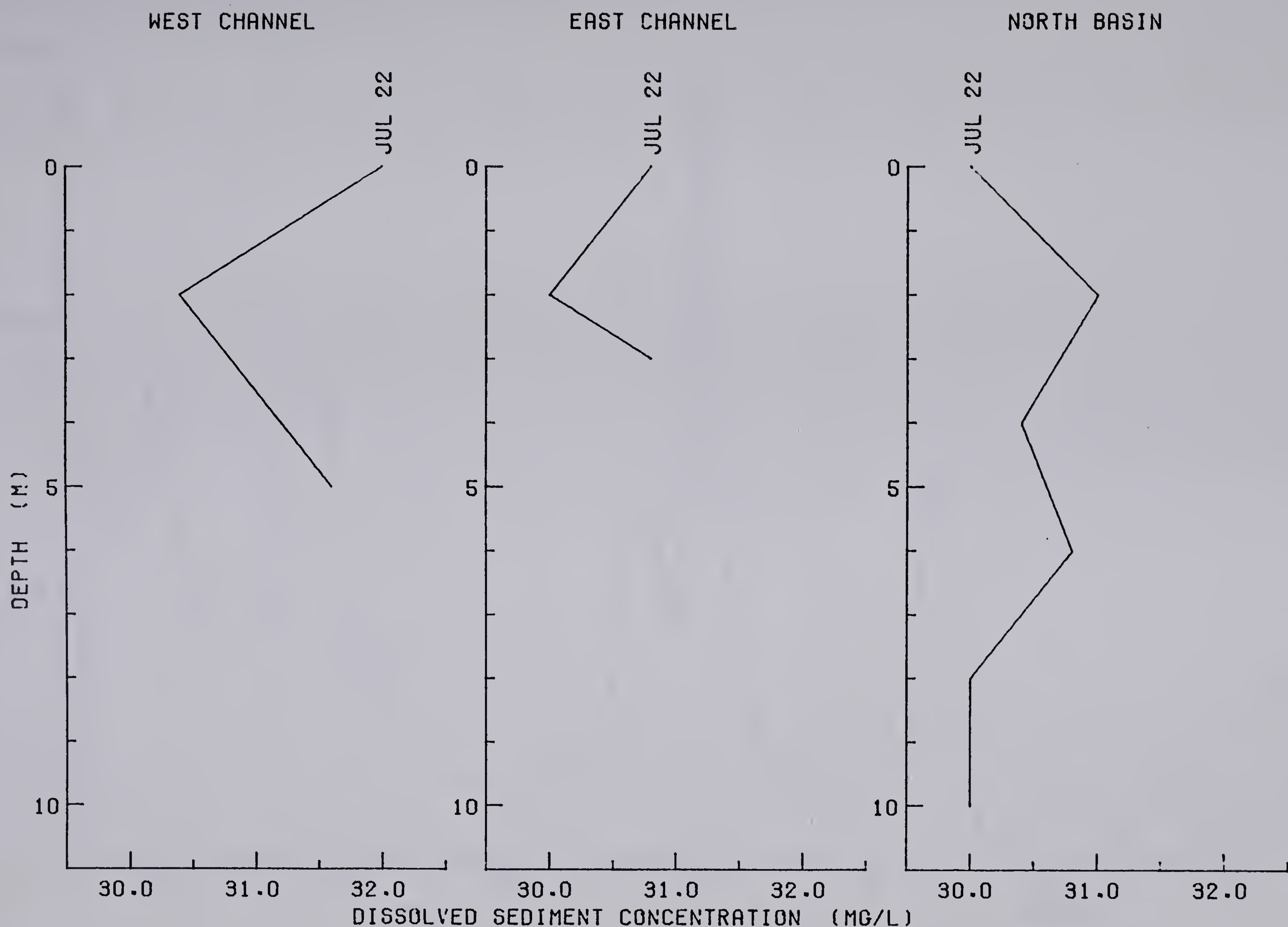


FIGURE 22B. DISSOLVED SEDIMENT CONCENTRATIONS IN SUNWAPTA LAKE FROM VAN DORN BOTTLE SAMPLES, JULY, 1975.

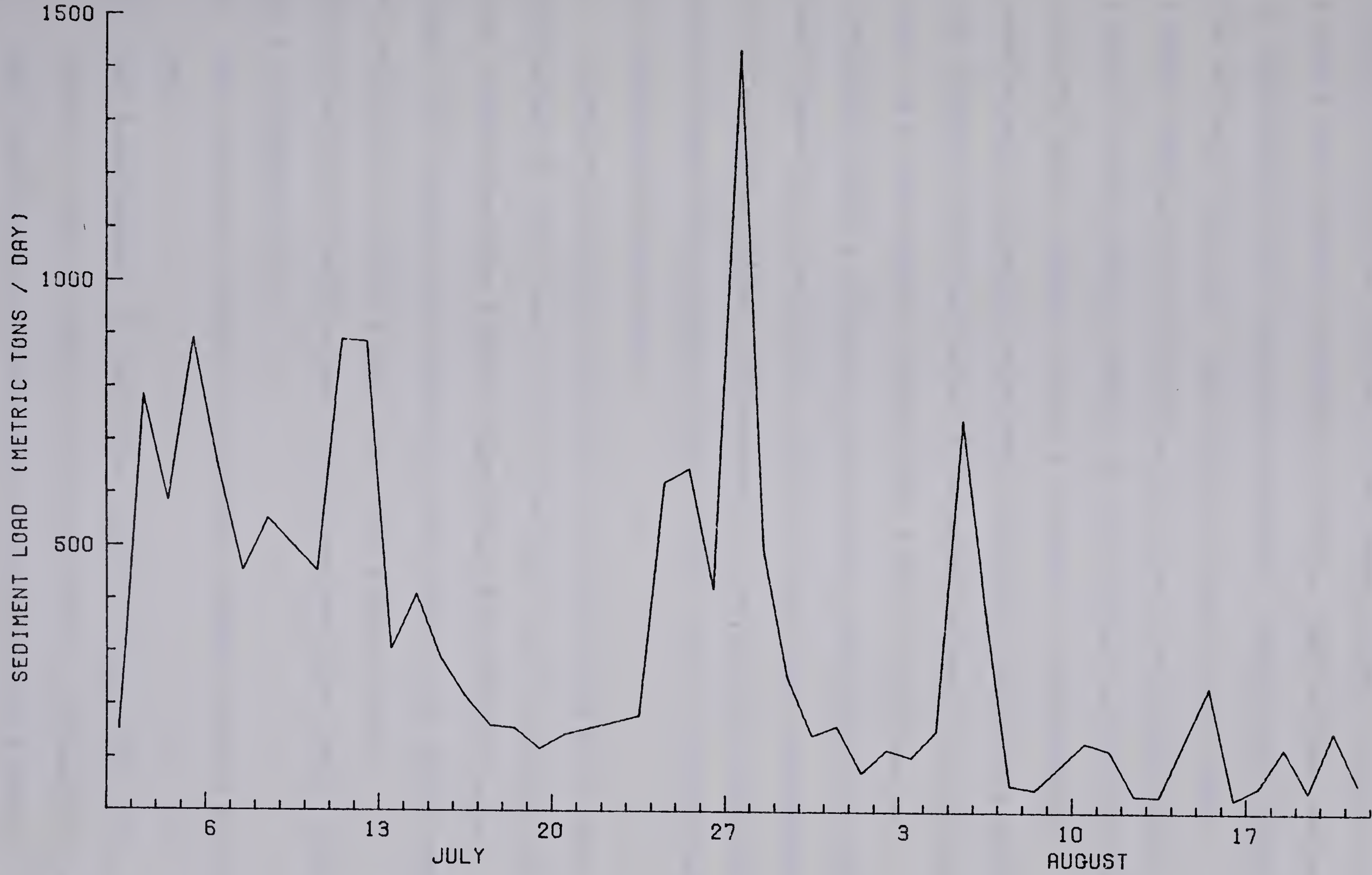


FIGURE 23. SEDIMENT LOAD IN THE SOUTHEAST STREAM, JULY 2 TO AUGUST 21, 1975.

glacier, a thaw and influx of sediment prior to break-up in mid-May was unlikely (Mathews, 1964a). Most of the sediment in suspension after freeze-up probably settled out during the winter. Since the lake did not freeze to its bed, inverse thermal stratification may have been established (Antevs, 1951; Smith, 1966). If so, thermal stratification may have had a slight and very temporary significance immediately following break-up. Inflowing meltwater, colder and lighter than the deeper lake water warmed by geothermal heat, may have spread through the lake as overflow or interflow. Such a situation of thermal stratification was of short duration; increasing sediment input soon outweighed the effects of slight differences in temperature. Katabatic winds caused overturning of lake water and the establishment of isothermal conditions.

Break-up occurred about May 17. From mid-May to the beginning of July, mean daily discharge in the outlet was low, suggesting low inflow discharge and sediment input (Fig. 17). Inflow was primarily nival melt. The small amount of sediment introduced into the lake was probably distributed by overflow and interflow over the south basin as a consequence of:

1. The temporary effects of inverse thermal stratification, and
2. The development of 'settling layers' within the lake. Prior to July 3, diurnal fluctuations in sediment input were very slight. Gradually the slow steady input of

sediment and the frequent agitation of wind and waves resulted in uniformity of suspended sediment concentration from lake surface to bed. The density of the lake water was increased by the presence of sediment particles, particularly in the south basin.

On June 20, observations showed sediment being dispersed over the surface of the south basin. Overflow plumes drifted through the channels into the north basin, converging in the vicinity of Pan 2. There was little evidence of subsurface flow. Underflows at this time were unlikely for the reasons already mentioned: slow nival melt resulting in low sediment input with little fluctuation, and gradual increase in lake water density due to rising suspended sediment concentration. Interflows, however, very likely occurred. The momentum of the influent stream water flowing southwest into the basin probably caused interflows and overflows to follow a preferred path towards the southwest and Pan C. When stream discharge was low, current momentum was low. Not only was lateral spreading intensified but the more rapid deceleration of current velocity caused deposition of more and finer material closer to the delta. When discharge increased in the afternoons and during periods of warm weather, current momentum was likewise increased. The higher sediment load was transported much greater distances.

Until July 3, sediment input was low, variations in sediment concentration very small, and periods of

undisturbed settling much longer than in summer. When interflows occurred above a settling layer, they were probably relatively deep within the south basin. Assuming the validity of Stokes' Law for clay-sized particles, a clay particle with a diameter of 2 microns and a density of 2.60 g/cm³ would require about 19 hours to fall 6m in calm water with a density of 1.0 g/cm³ and viscosity of 0.01 poises. Coarser particles would settle much faster. Therefore, in a period of 24 - 48 hours, a settling layer would have been established several metres below the depth of the west channel before the next sediment influx, particularly if the lack of wind and the formation of lake ice overnight kept the lake water calm. With rising air temperatures, the katabatic wind lasted from early morning to late afternoon and shortened periods of undisturbed settling. Interflows flowing above the settling layer and below the depth of the channels may have been wholly or partially blocked by the island and channel ridges and confined to the south basin. As lake water density increased, shallow interflows may have resulted from low to moderate sediment input. Van Dorn bottle samples near Pan B on July 17 and near Pan 2 on July 19 and 22 showed a gradual increase in suspended sediment with increasing depth (Fig. 22A). All these samples were collected during periods of relatively slow steady sediment input and decreasing discharge. For the period July 18 - 25, conditions in the lake with regard to suspended sediment concentration, and therefore density, were stable. On July

19, in particular, lake water concentrations appear almost uniform from surface to bed. With low sediment input, conditions favoured sediment distribution by interflow and overflow into the north basin. Distribution by interflow may partly account for the greater sedimentation rates for Pans 1, 2 and 3 for certain periods in the summer.

An increase in sediment concentration with depth in the lake may be due to interflow or to the existence of a settling layer. From July 6 - 10, the southeast stream discharge was high but measured sediment input only moderate. Surface concentrations in the south basin remained high and lake water density had increased since the end of June. On July 10, Van Dorn bottle samples in the west and east channels showed an increase in concentration with depth (Fig. 22A). On July 17, conditions remained the same for the west channel, except that concentrations were lower. In the east channel, the lowest concentration occurred at a depth of 2m. The slight increase in sediment concentration near the bed may have been the result of:

1. Sediment being disturbed and put back into suspension by currents or small nearby slumps, or
2. A settling layer from a previous sediment influx having cleared the middle depths before a new addition of sediment produced an overflow.

The presence of a surface water layer with a higher suspended sediment concentration than the water at a depth of 2m suggests overflow due to thermal stratification. A

change in water temperature from 0°C to 4°C increases water density by 0.000132 g/cm³ (Hodgeman, 1940); a change in suspended sediment concentration of 80 mg/l increases water density at 1°C to 0.9999498 g/cm³, an increase of 0.0001 g/cm³. If stream water at 0°C was flowing over lake water at 4°C, the difference in density between the two water layers (minus the increased density due to suspended sediment) would be only 0.000032 g/cm³. It is not likely the difference in water temperature was as great as 4°C, considering the proximal location of the east channel. A rise of 1°C would increase lake water density by 0.000059 g/cm³. The difference in density was probably in the order of 0.000041 g/cm³. The situation in the east channel as the July 17 Van Dorn bottle samples were being collected was probably one of relative equilibrium in density between the influent stream water and the water in the east channel. At this time, a powerful muddy current was flowing northwest towards the east end of the island. Current momentum and wind-generated turbulence kept surface sediment in suspension at the surface.

In the west channel, the highest concentration recorded on July 22 was at 4m. Since both discharge and sediment input were very low on the days prior to and including July 22, this increase in concentration with depth may represent the gradual settling of particles following a period of high, rapid sediment input. Alternatively, this increase may represent material being distributed by interflow. At this

time, stream channels were directing flow along the south side of the island towards the west channel.

Interflow conditions are proposed for July 22 on the basis of the vertical distribution of concentration. Concentrations declined from 70 mg/l at the surface to less than 62 mg/l at 2m. At 4m depth, concentration increased sharply to 164 mg/l, then decreased to 129 mg/l at 5m depth. Conditions were probably isothermal. Stream momentum directed the major portion of current flow towards the west channel and the slight increases in sediment input on July 21 and 22 may have been sufficient to produce interflows at about 4m depth. The fact that water with greater concentration, and therefore higher density, was flowing over west channel water of lower concentration may be the result of current momentum propelling the water through the channel. If the interflow flowed through the south basin at a depth below 6.5m, the depth of the west channel, it may have struck the channel ridge. Some material would have been deposited with the sudden loss of velocity. The remainder may have risen to a higher level in the channel. Alternatively, or in addition, the current may have been forced over irregularities in the channel floor.

At the distal end of the lake, the low sedimentation rates and fine-grained material of the Pan 4 samples suggest deposition solely from suspension (Fig. 24g). Given the geometry of the lake basin, Pan 4 was probably not affected by either underflows or interflows. Only material fine

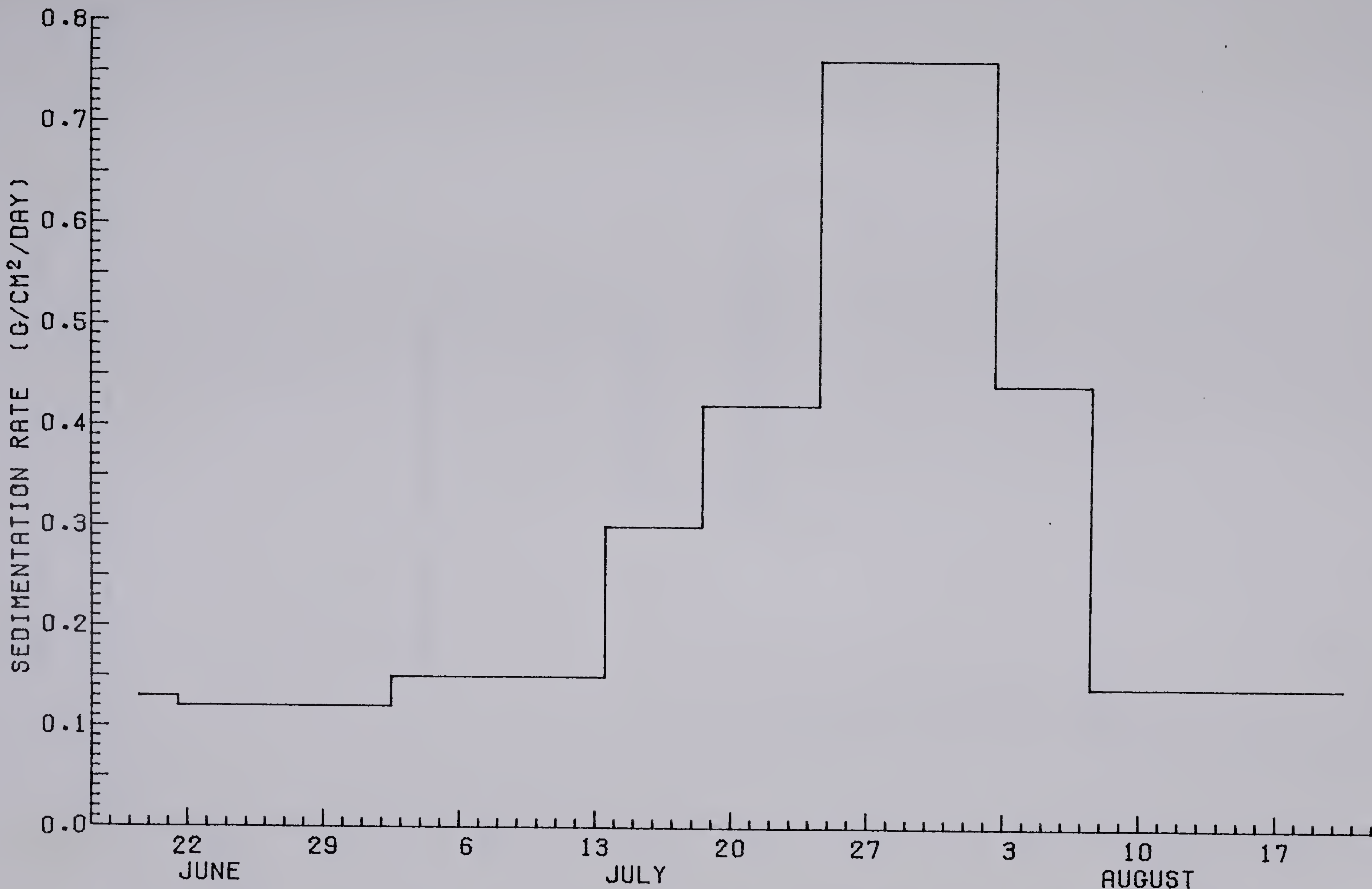


FIGURE 24A. SEDIMENTATION RATES FOR PAN A. JUNE 20 TO AUGUST 21, 1975.

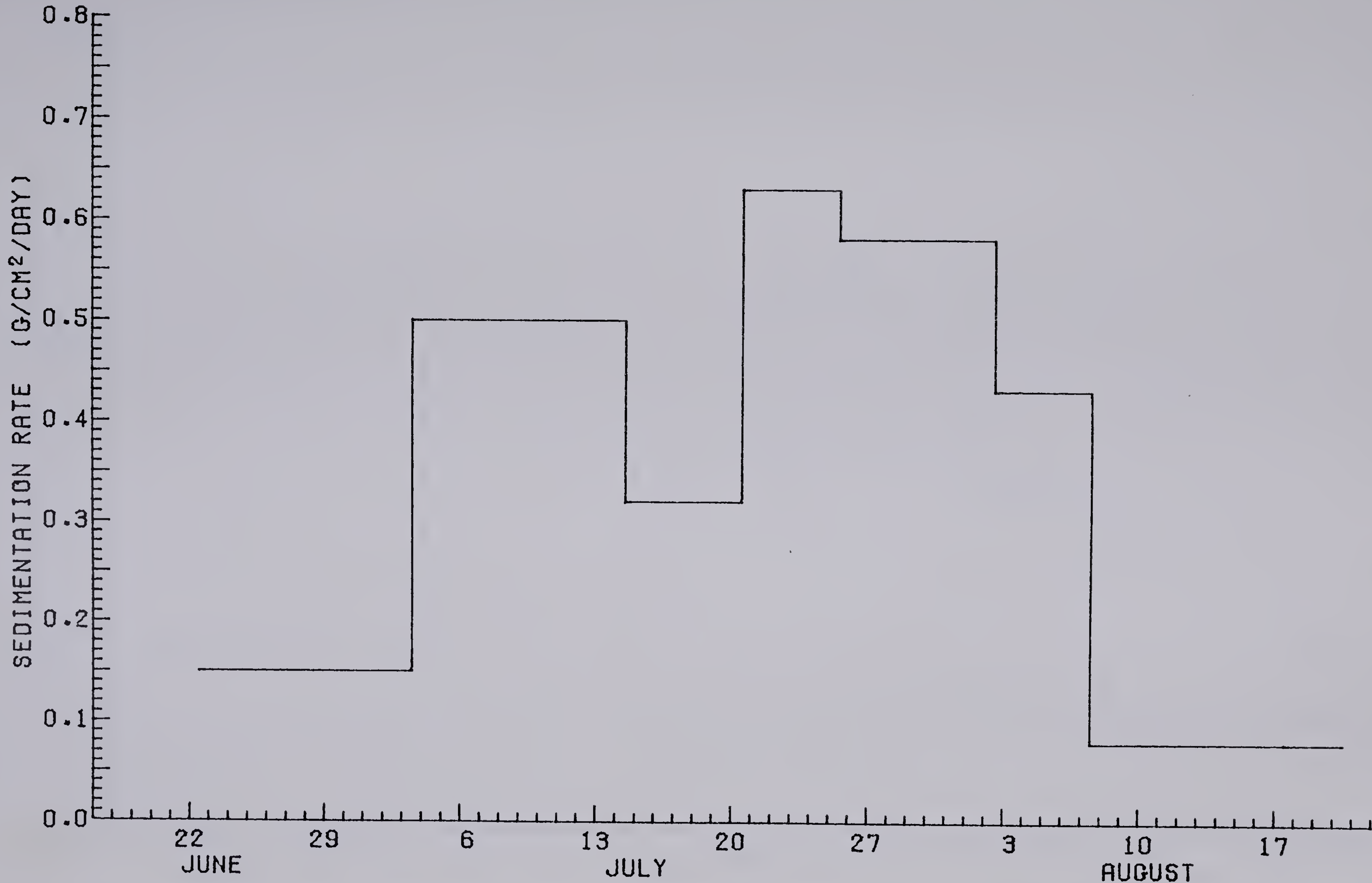


FIGURE 24B. SEDIMENTATION RATES FOR PAN B, JUNE 23 TO AUGUST 21, 1975.

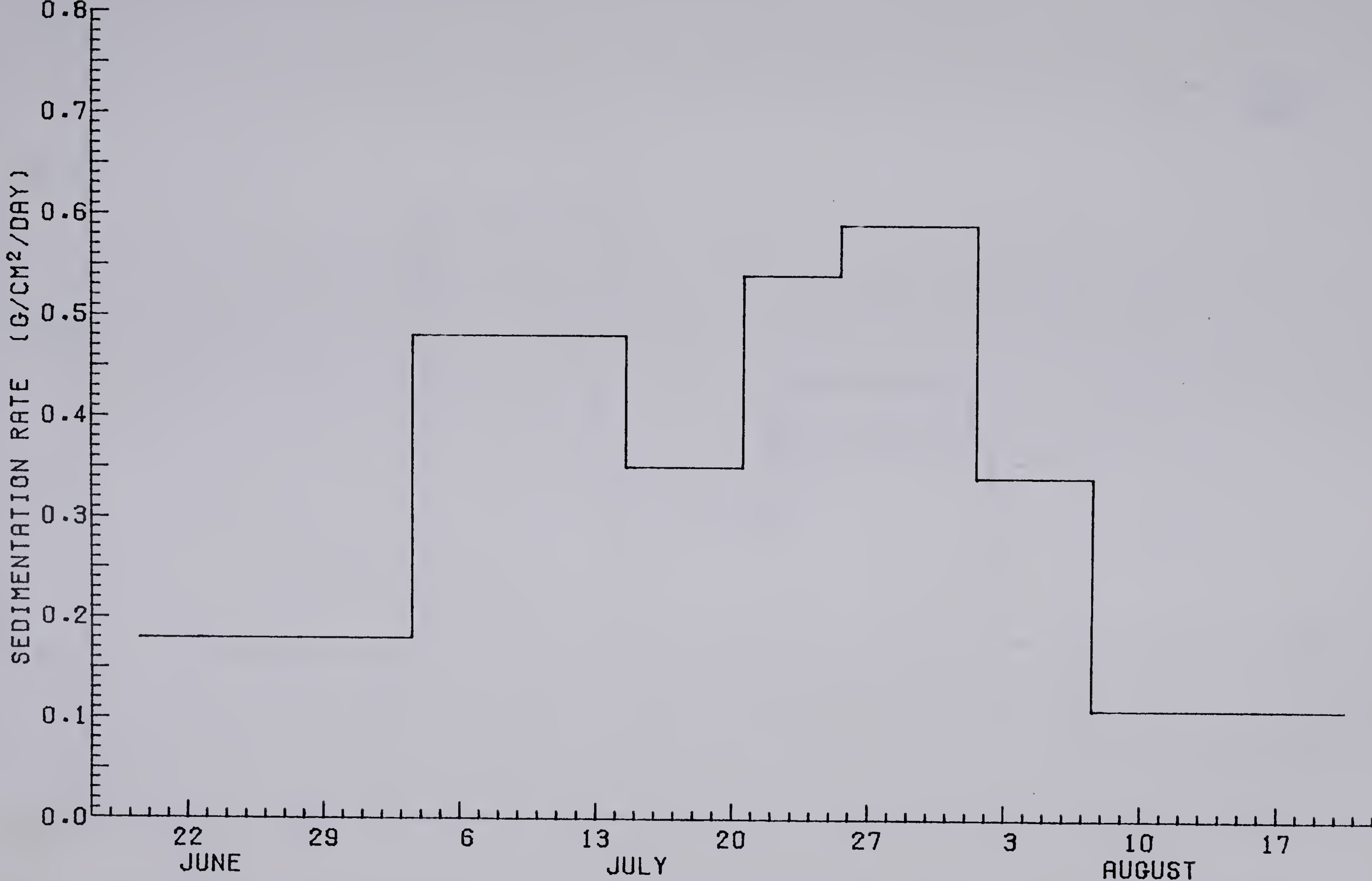


FIGURE 24C. SEDIMENTATION RATES FOR PAN C, JUNE 20 TO AUGUST 21, 1975.

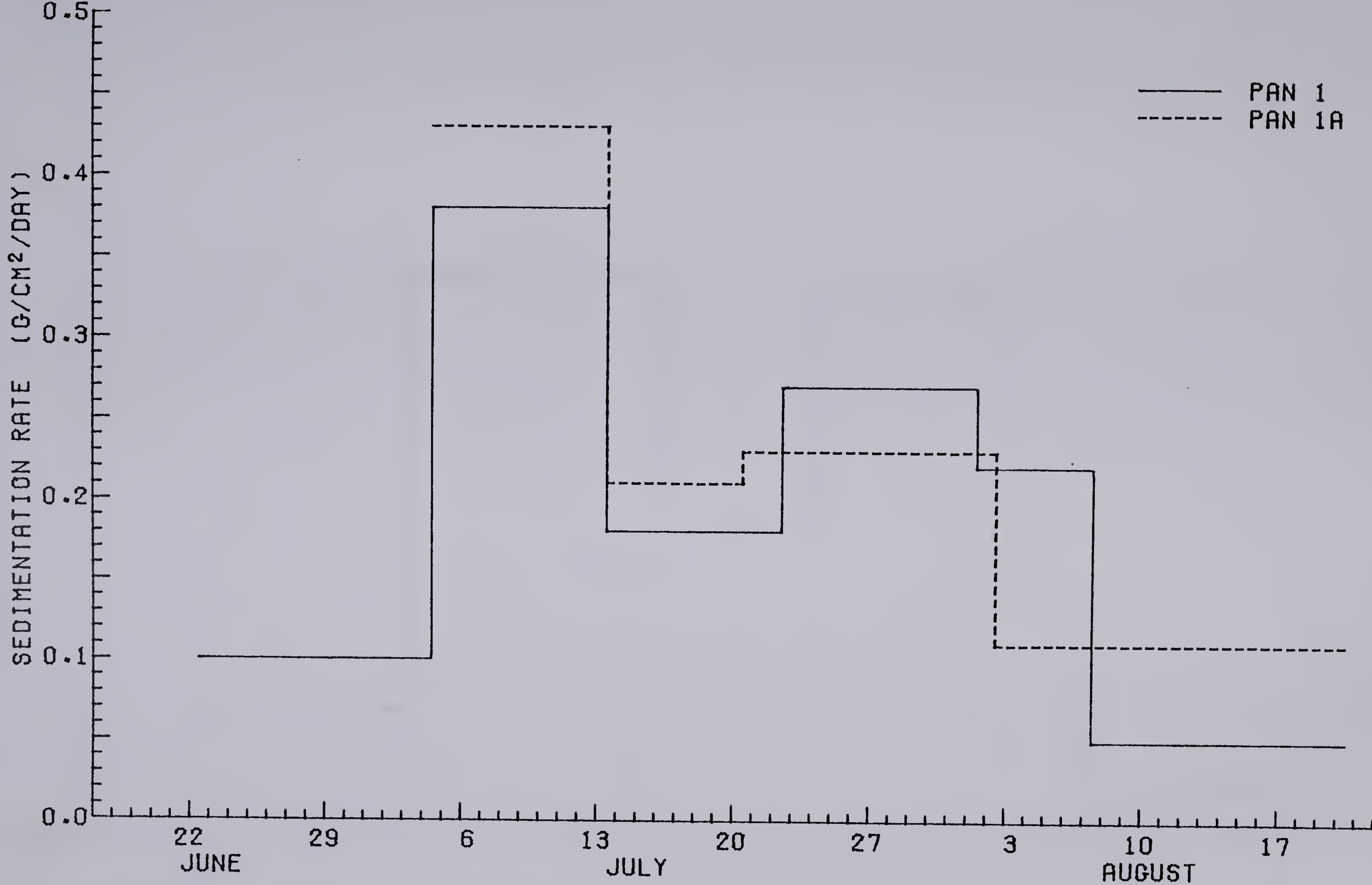


FIGURE 24D. SEDIMENTATION RATES FOR PAN 1, JUNE 23 TO AUGUST 21, 1975, AND PAN 1A, JULY 5 TO AUGUST 21, 1975.

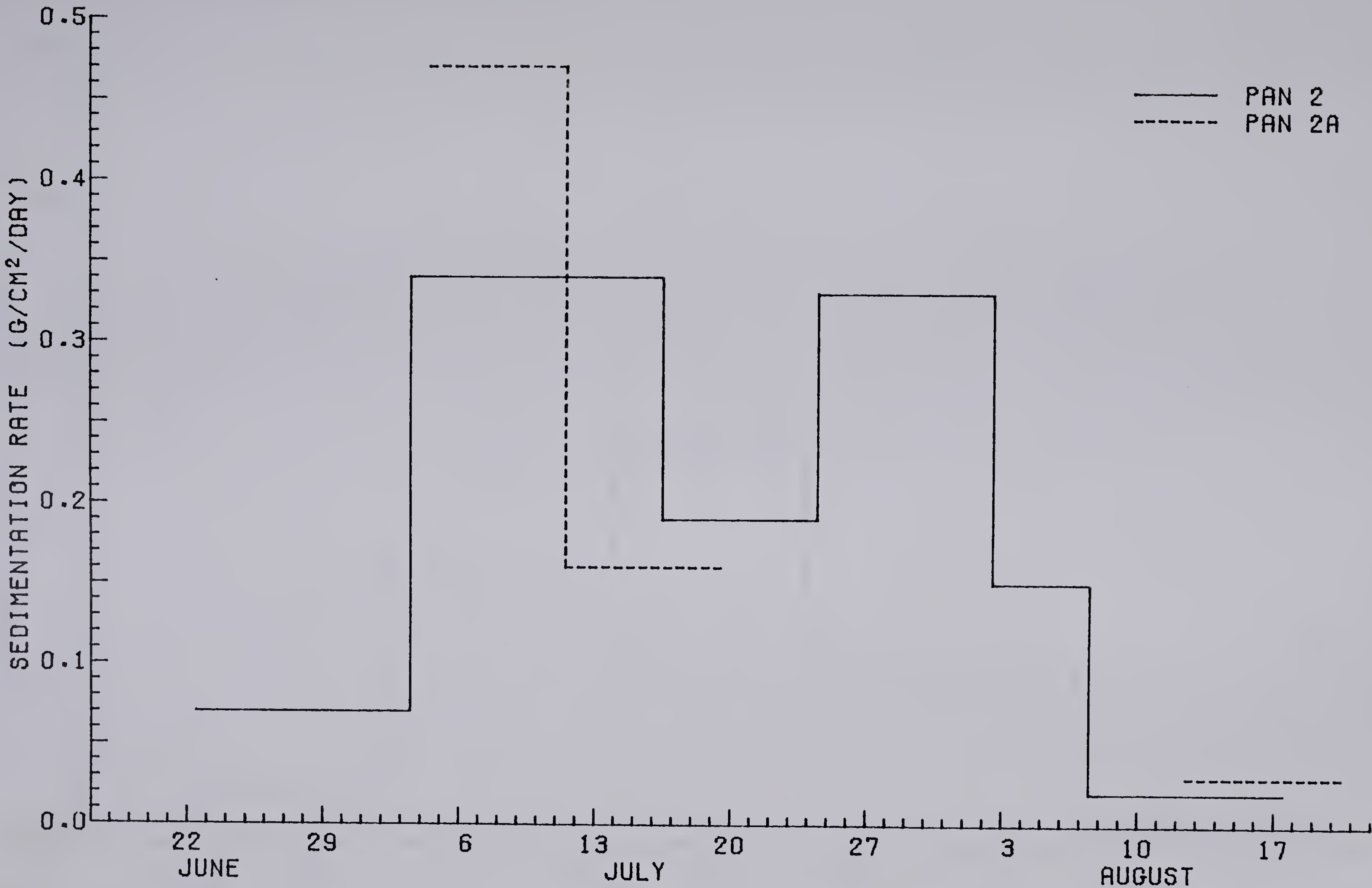


FIGURE 24E. SEDIMENTATION RATES FOR PAN 2, JUNE 23 TO AUGUST 18, 1975, AND PAN 2A, JULY 5 TO AUGUST 21, 1975.

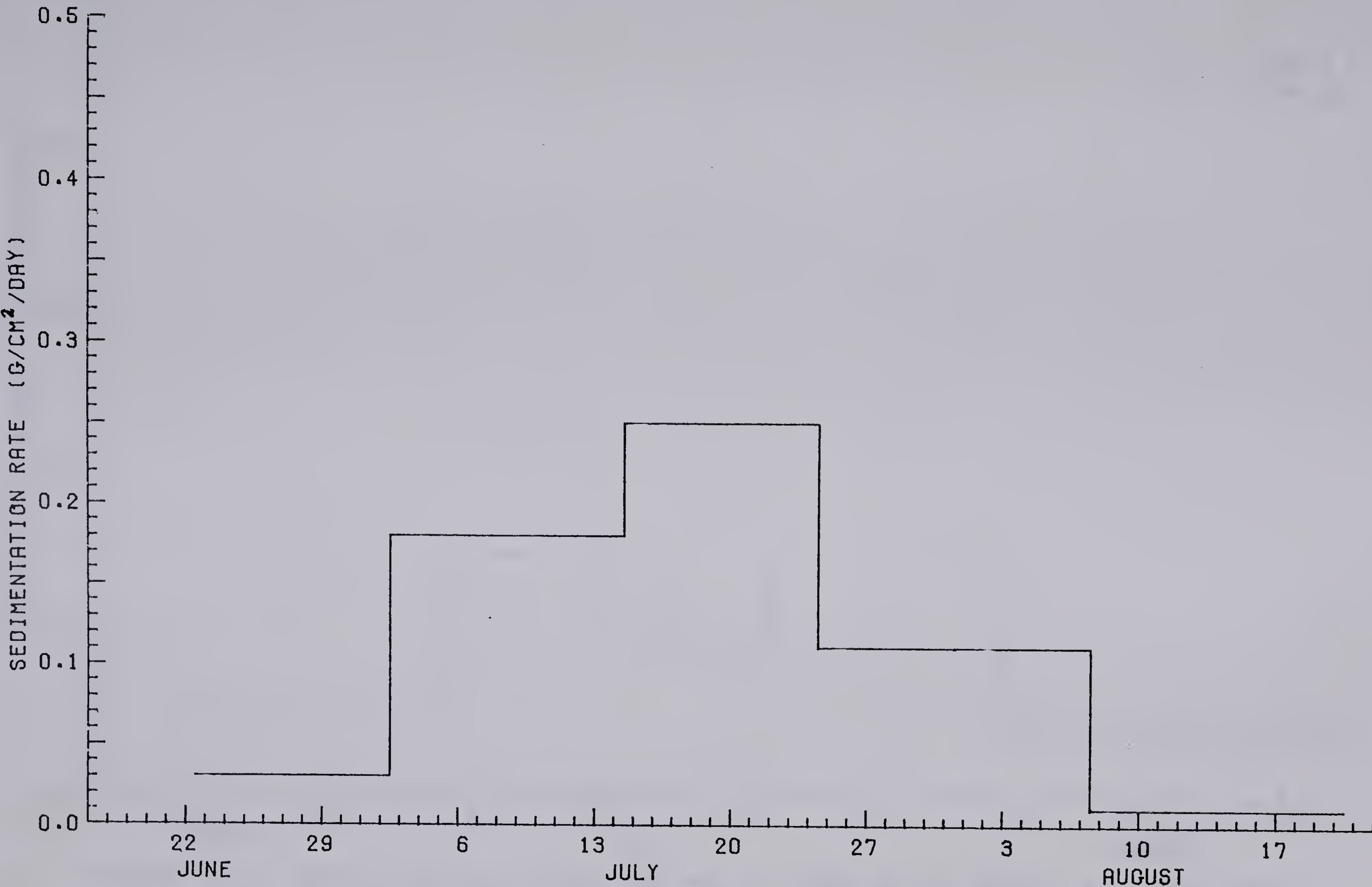


FIGURE 24F. SEDIMENTATION RATES FOR PAN 3. JUNE 23 TO AUGUST 21. 1975.

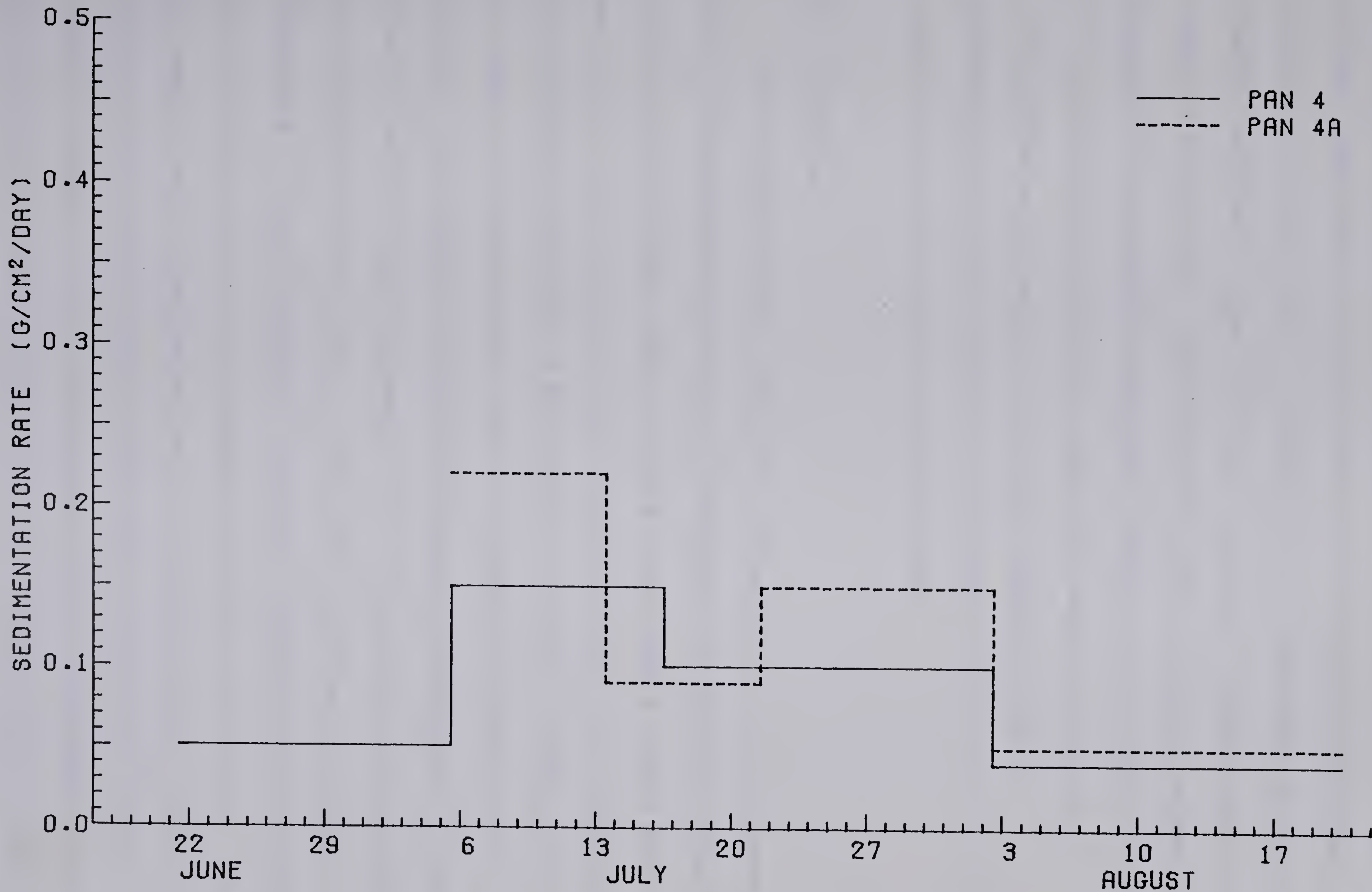


FIGURE 24G. SEDIMENTATION RATES FOR PAN 4, JUNE 22 TO AUGUST 21, 1975, AND PAN 4A, JULY 6 TO AUGUST 21, 1975.

enough to be transported by overflow reached the distal end of the lake. Sedimentation rates for Pan 4 did increase for July 6 - 17 and July 17 - August 3, a reflection of the greater sediment input from the southeast stream, and to a lesser extent, some input from the Mt. Athabasca stream. The proportion of overflow sediment reaching Pan 4 was increased by turbulence in the lake; katabatic winds generally accompanied warm weather and high sediment input. Sedimentation rates for Pan 4 were much lower for most of August when cool weather predominated.

B. Underflow

The sudden large influx of sediment on the afternoon of July 3 represented the first 'flushout' of deposits from the previous year (Fig. 19A). Discharge was still relatively low and inflow was probably nival meltwater with high competency and capacity (Kennedy, 1975; Sugden and John, 1976). Since the July 3 concentration was the highest recorded in the summer, the sediment could not have been deposited in the time interval since break-up; outlet discharge records give no indication of any flow event that could be associated with such a large influx of sediment. Surface concentrations in the south basin on the evening of July 2 were less than 200 mg/l. Water density at 1°C is 0.999900 g/cm³. With a concentration of 200 mg/l, lake water density was about 1.000025 g/cm³. In the north basin, surface concentrations were among the lowest recorded of the season (Fig. 21A). At

greater depths, concentrations may have been somewhat higher but the turbulence generated by wind and inflowing water probably kept the lake water uniform in terms of suspended sediment. The concentration sampled in the southeast stream on the afternoon of July 3 was over 3100 mg/l. Stream water density was about 1.00183 g/cm³. Differences in density between stream and lake water may have been as high as 0.00181 g/cm³. Since turbidity underflows have been known to continue flowing with density differences as small as 0.0005 g/cm³ (Bell, 1942), it seems likely that an underflow event occurred on July 3. The low surface concentrations in the north basin on July 3, 4 and 5 suggest sediment distribution by deep subsurface flow and not by overflow or shallow interflow. Surface concentrations in the south basin were very high on July 4, and in the west channel rose to 275 mg/l on the morning of July 5. Sediment input was still relatively high, but the large discrepancy in density between lake water and stream water no longer existed. Overflow and interflow were more likely to occur. Another exceptionally large influx of sediment took place on July 5. An underflow event was still possible, although density differences between stream and lake water were not as great.

Several other occasions on which conditions were conducive to underflow activity occurred on July 24, July 27 and August 5. The sudden large input of sediment on July 24 and again on August 5 followed periods of relatively low discharge and sediment concentration in the stream and lake

water (Fig. 19A). Lake water was comparatively 'sediment-free' although not as clear as in the spring. In the south basin, the sedimentation rates at Pans B and C for July 21 - 26 almost doubled the rates for July 15 - 21 at the same sites (Fig. 24B and 24C). The latter period was one of low discharge and sediment input. The higher rates for July 21 - 26 may reflect not only the greater discharge and sediment input but also deposition from one or more underflow events. If a large proportion of material was being distributed by underflow, this might explain why sedimentation rates for the north basin, although high, were not the highest of the summer as were rates for the south basin pans.

Pans A, B, and C in the south basin and Pans 1 and 3 in the west and east channels respectively were placed in areas of possible underflow activity. This was particularly true for Pan A. In the south basin, turbidity underflows probably resulted from differences in density due to suspended sediment. They may also have been generated by slumping on the steep foreset beds of the east delta. Fifteen to twenty metres from the mouth of the southeast stream, the steep foreset beds give way to the relatively flat floor of the basin. The sudden reduction of velocity 'head' and consequent loss of velocity should have resulted in heavy sediment deposition in the area of Pan A. However, if underflows were following a preferred path, with little lateral spreading, down the delta front and beyond, Pan A

might easily have been bypassed. It may be significant that for the one recorded period in which the sedimentation rate of Pan A exceeded the rates at Pan B and Pan C (July 25 - August 3), the major flow from the southeast stream was directly towards Pan A. At other times, stream flow was predominantly southwest (spring and early summer) or northwest towards the island (mid-and late-summer).

With the establishment of a north-flowing stream branch on the east delta, the opportunity existed for underflow activity in the north basin. At the beginning of August, the weather turned cool, mean daily discharge for the southeast stream was relatively low and the lake water appeared clearer than usual. The latter observation was supported by the low surface concentrations of suspended sediment for all pan sites except B and 1 (Fig. 21A). On the afternoon of August 5, after a period of relatively low sediment input, the suspended sediment concentration of the southeast stream rose to over 1900 mg/l (Fig. 19A). Suspended sediment load for that day was estimated at over 740 metric tons. Surface concentrations rose at all the pan sites in the afternoon. A very definite sediment-laden current was observed flowing north into the north basin; several metres beyond the stream mouth, the muddy water appeared to 'plunge' beneath the lake water. At this time, the estimated density differences between stream and lake surface water due to suspended sediment were probably of the order 0.001058 g/cm³. Because of the high density of the stream water relative to the lake

water, an underflow event possibly occurred immediately north of the east channel. Although the sedimentation rate of Pan 3 was the lowest of the three intermediate pans (Pans 1,2 and 3), this may have been the result of one or more of the following:

1. Pan 3 did not lie on the preferred path of the underflow and was bypassed (the east channel ridge slope is steep and irregular),
2. Sediment already deposited in the pan was washed out by a high-velocity flow,
3. The pan was too close to the source for deposition to occur, or
4. The sides of the pan disrupted flow, either splitting the current or encouraging deposition on the upstream or downstream side rather than in the pan.

Pans 1 and 3, and to some extent Pan B, may have been affected by slump-generated underflows originating on the channel ridges or the Mt. Athabasca stream delta. These would not have influenced the other south basin pans. Underflows caused by slumping or by sediment input from currents flowing into the east channel may account for the high sedimentation rate at Pan 3 during the period July 18 - 25.

As a general rule, sediment was distributed by overflow and interflow in the morning and during times of low sediment input. Turbidity underflows probably occurred in the afternoon when a sudden large influx of suspended

sediment followed a period of low discharge and relatively low sediment input. Conditions favouring turbidity underflows generated by density differences were relatively rare in Sunwapta Lake during the field season of 1975, occurring at most three or four times. The incidence of slump-generated underflows could not be determined but was probably higher.

C. Slumping

The disappearance of Pan 3A and its replacement, and the disturbance of Pan 3 on several occasions during the 1975 field season suggest slumping as an agent of sediment distribution in Sunwapta Lake. Three major factors existed conducive to slump occurrence in the lake:

1. Rapid deposition of suspended sediment,
2. High-angle slopes, and
3. Fluctuating water levels.

The slopes of the south basin, the island and channel ridges, and the deltas have gradients ranging from 9.5° in the east channel to over 25° on the foreset beds of the main deltas. Slumping has been known to occur on slope inclinations of 1 - 3° in areas of rapid deposition and unconsolidated sediments (Morgenstern, 1967). Both conditions existed in Sunwapta Lake. The daily suspended sediment load of the southeast stream was high throughout July and August, ranging from an estimated 39 metric tons to over 1400 metric tons (Fig. 23). Periods of high sediment

input were also periods of high velocity currents that carried much of the fine-grained material - fine silt and clay - beyond the zone of rapid deposition. Consequently, a small proportion of clay relative to sand and coarse silt was deposited on the delta and ridge slopes during high flow events.

It seems highly probable that slumping occurred in Sunwapta Lake on the delta fronts and on the channel ridges. Slumps may have been generated by rising seepage pressure as lake levels fell (Andresen and Bjerrum, 1967). Lake levels varied as much as 0.33 to 0.5m, both diurnally and between high and low flow stages. It was not unusual for several days of warm weather with high sediment input and high lake levels to be followed by cool weather, relatively low sediment input and rapidly falling lake levels. On the deltas, pore water pressure was augmented by groundwater flow. Slumping may also have been initiated by liquifaction of rapidly deposited fine sand. Beds of loose fine sand were present on the deltas after peak flow events. The triggering mechanism could have been the movement of people and vehicles (particularly on the east delta), ice or large stones carried down by the stream, the action of lake ice along the shore, or the occurrence of slumping on other parts of the delta.

Both Pan 3 and Pan 3A were placed north of the east channel on the slope of the east ridge. In July and August, temporary north and northeast-trending stream channels were

established on the east delta. Since these stream channels were usually active during periods of high discharge and suspended sediment load in the southeast stream, sediment input directly into the east channel and north basin was greatly augmented. Flow occurred in north-trending stream channels in mid-July. On July 15, Pan 3 was brought up from the lake bed and from its contents a sedimentation rate was calculated to be only half that of Pans 1 and 2. Sometime between the morning of July 15 and the morning of the 16th, Pan 3A disappeared. At this time the weather was cool, cloudy and very wet, the east delta stream discharge was dropping, and lake levels were much lower than previously during the hot weather and high discharge prior to July 14. A north-trending stream channel was re-established about July 24. When Pan 3 was recovered on July 25, it was full of mud and sand with the largest proportion of coarse material on the upslope side of the pan. The sedimentation rate recorded at Pan 3 for this period (July 14 - 25) was the highest for the north basin pans (Fig. 24D - 24G). On July 29, the replacement for Pan 3A disappeared. Finally, on August 1, Pan 3 was found to be empty and tilted to one side. This also occurred while muddy water was being discharged directly into the north basin. For the remainder of August, only the west-flowing stream branches were active. The events described above suggest a series of slumps on the east ridge following rapid deposition from temporary north-flowing stream branches. Once in motion,

momentum carried the material down the high-angle slope to the flat-floored basin. During periods in which these stream channels were inactive, neither Pan 3 nor Pan 3A appeared to be disturbed. Slumping would also account, wholly or in part, for the great thickness of sediment deposited in the north basin, immediately north of the island and ridges (Gilbert, 1975a). In addition, particle size analysis indicated that a significant proportion (greater than 10 percent) of sediment coarser than 4_ϕ was present in a sediment pan sample recovered from the Pan 3 site on August 21 (Appendix 4). The pan was on the lake bed from August 8 - 21, the period of lowest sediment input for the field season. However, slumps and slump-generated underflows were likely to occur at this time. By contrast, the only material coarser than 4ϕ present in the other north basin sediment pan samples was found in the Pan 1 and Pan 1A samples for the first three weeks of July, the period of highest sediment input for the melt season and the time when turbidity underflows and interflows were most likely to occur.

Evidence of slumping in the south basin was complicated by the rapid sedimentation rates and high probability of turbidity underflow events. However, since the conditions conducive to slumping which existed in the east channel were intensified and almost continuous on the east delta front, it is very likely that slumping occurred frequently in the south basin. Slumping may also have taken place from the

island and ridges into the south basin. The breaking of subsurface currents against the ridges, with the resulting sudden loss of capacity, probably increased rates of deposition in this area. Immediately south of the west channel, water from both the southeast and southwest streams converged and flowed through the channel. A certain amount of the thick sediment south of the west channel may be slump material from the west ridge.

Pans 1 and 1A in the west channel showed no evidence of slumping. However, an echo sounder had been used to ensure that Pan 1 was not adjacent to high-angle slopes. Both Pan 1 and Pan 2 in the north basin may have been affected by a phenomenon often associated with subaqueous slumps - the generation of a turbidity underflow (Morgenstern, 1967; Hampton, 1972; Gilbert, 1975b). Such underflows may have originated on the west delta, the ridges or the Mt. Athabasca stream delta. The thick band of sediment extending west from the latter delta (Gilbert, 1975a) may have been related to slump-generated underflows, particularly in the years when the Mt. Athabasca stream was more active. From the general morphology of the deposits, it appears that underflows travelled down the delta front towards the flat floor of the basin. Momentum then carried some flow up the gentle reverse slope on the west side of the deep centre basin, as much as 100m from the delta. At this point, velocity reduction and sediment deposition resulted in dissipation of the current. Slump-generated

underflows from the Mt. Athabasca stream delta may account in part for the very high sedimentation rates at Pan 2 for July 7 - 17 and July 26 - August 3 (Fig. 24E). During the hot weather of those periods the Mt. Athabasca stream was active. The steep delta front, the increased stress exerted by swift-flowing currents during high flow stages, and the sudden and rapid deposition of sediment combined to create a situation favouring slumping. Pans 2 and 2A were situated in an area likely to be affected by underflow deposition from the ridges and the Mt. Athabasca stream delta.

Any slump events that occurred had only local effects, while slump-generated turbidity underflows in the north basin may have distributed sediment as far as the distal end of the lake.

3.4.4 Sedimentation in Sunwapta Lake

On June 22 and 23, the seven large sediment pans were placed in the lake (Fig. 6). That a major influx of sediment occurred before the 22nd seems unlikely for several reasons:

1. The low mean daily discharge at the outlet. Prior to July 2, only outlet (Sunwapta River) discharge records are available. These reveal little flow, less than 1.5 cms, until June 23 (Fig. 17) indicating low influent discharge at this time. In general, a positive correlation exists between discharge and suspended sediment concentrations (Fig. 20A).
2. Clean snow still covered much of the glacier. Low stream

flow resulting largely from nival melt would contain little suspended sediment.

3. In the late afternoon of July 3, what was probably the first 'flushout' of previous unconsolidated streambed deposits increased southeast stream concentrations to almost 3200 mg/l (Fig. 19A). If so, this would suggest that no high flow events had occurred prior to July 3 and that the influx of water on that day was relatively clean nival meltwater. Break-up took place in mid-May. However, July 3 marked the first really hot weather and large-scale melting of the melt season.

From the end of June until August 21, the pans were left on the lake bed for approximately corresponding intervals ranging in length from a few days to more than two weeks (see Tables 1A and 1B). From the sediment collected in the pans, sedimentation rates were estimated for each of the pan sites (Fig. 24A - 24G). Tables 4A and 4B show the sedimentation rates calculated for each pan.

From the sedimentation rates calculated for the seven pans, it is possible to divide Sunwapta Lake into at least three sedimentation zones. A similar division by Mathews (1964b) based on his research on Sunwapta Lake and River in 1957 revealed a decrease in rate of sedimentation with increased distance from the sediment source (Fig. 25). In 1957, both the southeast stream and the Mt. Athabasca stream entered the southeast corner of the north basin; this was the zone of rapid sedimentation (Zone A), with an estimated

Table 4A. Rates of sedimentation for each large sediment pan.

Pan	Sedimentation period	sedimentation rate g/cm²/day
1	Jun 23 - Jul 5	0.1008
	Jul 5 - Jul 14	0.3796
	Jul 14 - Jul 23	0.1780
	Jul 23 - Aug 2	0.2689
	Aug 2 - Aug 8	0.2228
	Aug 8 - Aug 21	0.0487
2	Jun 23 - Jul 4	0.0696
	Jul 4 - Jul 17	0.3448
	Jul 17 - Jul 25	0.1921
	Jul 25 - Aug 3	0.3280
	Aug 3 - Aug 8	0.1538
	Aug 8 - Aug 18	0.0219
3	Jun 23 - Jul 3	0.0312
	Jul 3 - Jul 15	0.1819
	Jul 15 - Jul 25	0.2453
	Jul 25 - Aug 1	0.1064*
	Aug 1 - Aug 8	0.1113
	Aug 8 - Aug 21	0.0117
4	Jun 22 - Jul 6	0.0456
	Jul 6 - Jul 17	0.1510
	Jul 17 - Aug 3	0.1023
	Aug 3 - Aug 21	0.0369

*Estimated

Table 4B. Rates of sedimentation for each large sediment pan.

Pan	Sedimentation period	sedimentation rate g/cm²/day
A	Jun 20 - Jun 22	0.1316
	Jun 22 - Jul 3	0.1161
	Jul 3 - Jul 14	0.1495*
	Jul 14 - Jul 19	0.3019
	Jul 19 - Jul 25	0.4164
	Jul 25 - Aug 3	0.7644
	Aug 3 - Aug 8	0.4394
	Aug 8 - Aug 21	0.1351
B	Jun 23 - Jul 4	0.1527
	Jul 4 - Jul 15	0.4959
	Jul 15 - Jul 21	0.3229
	Jul 21 - Jul 26	0.6302
	Jul 26 - Aug 3	0.5772
	Aug 3 - Aug 8	0.4322
	Aug 8 - Aug 18	0.0795
	Aug 18 - Aug 21	0.0826
C	Jun 20 - Jun 23	0.1804
	Jun 23 - Jul 4	0.1828
	Jul 4 - Jul 15	0.4841
	Jul 15 - Jul 21	0.3475
	Jul 21 - Jul 26	0.5352
	Jul 26 - Aug 2	0.5921
	Aug 2 - Aug 8	0.3361*
	Aug 8 - Aug 21	0.1139

*Estimated

FIGURE 25

SEDIMENTATION ZONES IN SUNWAPTA LAKE, 1957

SOURCES:	1974 SURVEY (GILBERT, 1975a)
	Mathews, 1964
SCALE :	1cm: 15.6m

LEGEND

A - ZONE OF RAPID SEDIMENTATION

(Sedimentation rate 0.5 $g/cm^2/day$)

B - ZONE OF MODERATE SEDIMENTATION

(Sedimentation rate 0.01 $g/cm^2/day$)

C - ZONE OF SLOW SEDIMENTATION

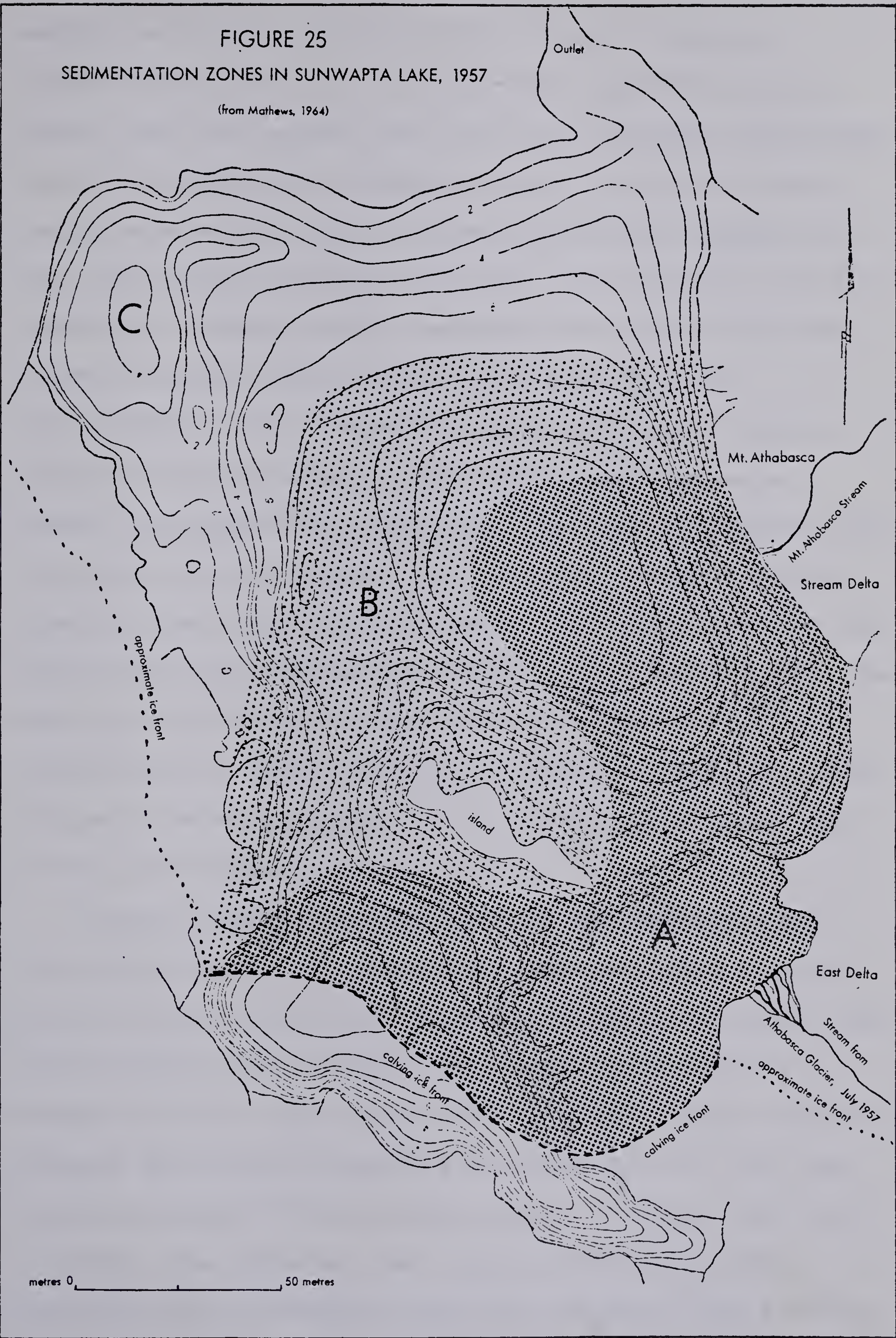
(Sedimentation rate 0.001 $g/cm^2/day$)

isobath interval : 1m

FIGURE 25

SEDIMENTATION ZONES IN SUNWAPTA LAKE, 1957

(from Mathews, 1964)



average rate of 0.5 g/cm²/day. The area of moderate sedimentation (Zone B), 0.1 g/cm²/day, included the west channel and the northern part of the north basin below 4.5m depth. The north and northwest part of the lake was the distal zone and the area of slow sedimentation (Zone C). Here, the average sedimentation rate was estimated as 0.01 g/cm²/day. Mathews (1964b) included most of what was then a somewhat smaller south basin in the zone of rapid sedimentation. The proximal location of the south basin justified its inclusion in the rapid deposition zone. However, if major stream flow was consistently directed into the north basin throughout the 1957 melt season, density underflows may have been confined to the north basin by the shallowness and configuration of the east channel ridge. The result may have been a higher sedimentation rate and deposition of a larger proportion of coarse material in the proximal zone of the north basin than in the proximal zone of the south basin.

Sunwapta River discharge records for 1957 show mean daily discharge to have been well below the average mean daily flow for the period 1948 - 1972 (Gilbert, 1975a). This would suggest below average inflow and possibly below average sediment input during the 1957 melt season. Mathews' sediment pans were on the lake bed from July 21 - 23, the period of highest flow in July. August discharge was higher but never rose above 4.5 cms. By contrast, mean daily discharge for the Sunwapta River in 1975 from July 4 - 18

inclusive never fell below 4.5 cms (Fig. 18). Although the correlation between discharge and suspended sediment concentration is rather low (Fig. 20A), the initial response to an increase in discharge, based on 1975 discharge and concentration data in the southeast stream, appears to be a rapid increase in suspended sediment concentration (Fig. 19A - 19C). This relates to streambed erosion. Periods of cool temperatures and low flow may result in deposition on the streambed. Once unconsolidated deposits have been removed by rising discharge, concentration falls; further sediment input results largely from the melting of dirty glacier ice. Consequently, the variability in discharge may be almost as important as the actual daily discharge in terms of suspended sediment load. In July and August, 1975, mean daily discharge calculated for the southeast stream ranged from 2.2 cms to over 8 cms. Three periods of very high flow alternated with periods of low flow and low sediment input (Fig. 19A). Mathews' (1964b) calculations of sediment input and sedimentation are based on a 42 - 46 hour period in 1957. Similar calculations for the 1975 melt season include periods of very high flow and sediment input as well as periods of relative inactivity. This would have a modifying effect on estimated sedimentation rates. It is, therefore, not surprising that the estimated rate of sedimentation in what was then (1957) the proximal zone was 1.5 - 2 times higher than the average rates estimated for the south basin pans for June 20 - August 21, 1975. Average daily rates per

pan for the latter period were:

1. Pan A - 0.2155 g/cm²/day

2. Pan B - 0.3341 g/cm²/day

3. Pan C - 0.3176 g/cm²/day

Sedimentation rates per pan for shorter periods during the 1975 melt season were often much higher (see Table 4B). These reflect the higher and more variable discharge for certain periods in 1975 as compared with that of late June to September, 1957.

By 1975, the proximal zone of the lake was largely confined to the south basin (Fig. 26). The zone of rapid sedimentation was considered to be the south basin below 4m depth, except around the southeast and southwest deltas where the streams entered the lake. The west channel was not included since increased flow through the restricted channel and increased distance from the source probably reduced deposition in this area. The average rate of sedimentation for the three south basin pans during the recorded period was estimated as 0.289 g/cm²/day. Sediment accumulation for this period was estimated as 16 - 18 g/cm². Total accumulation for June 20 - August 21 for Zone A, with an area of 0.021km², was calculated as 3,400 - 3,800 metric tons.

Zone B, the area of moderate sedimentation, consisted of the north basin below a depth of 6m except in the southeast. Calculations and estimates for Pans 1, 2 and 3 showed roughly similar average sedimentation rates for the

FIGURE 26

SEDIMENTATION ZONES IN SUNWAPTA LAKE, 1975

SOURCE: 1974 SURVEY (GILBERT, 1975a)

SCALE : 1cm : 15.6m

LEGEND

A - ZONE OF RAPID SEDIMENTATION

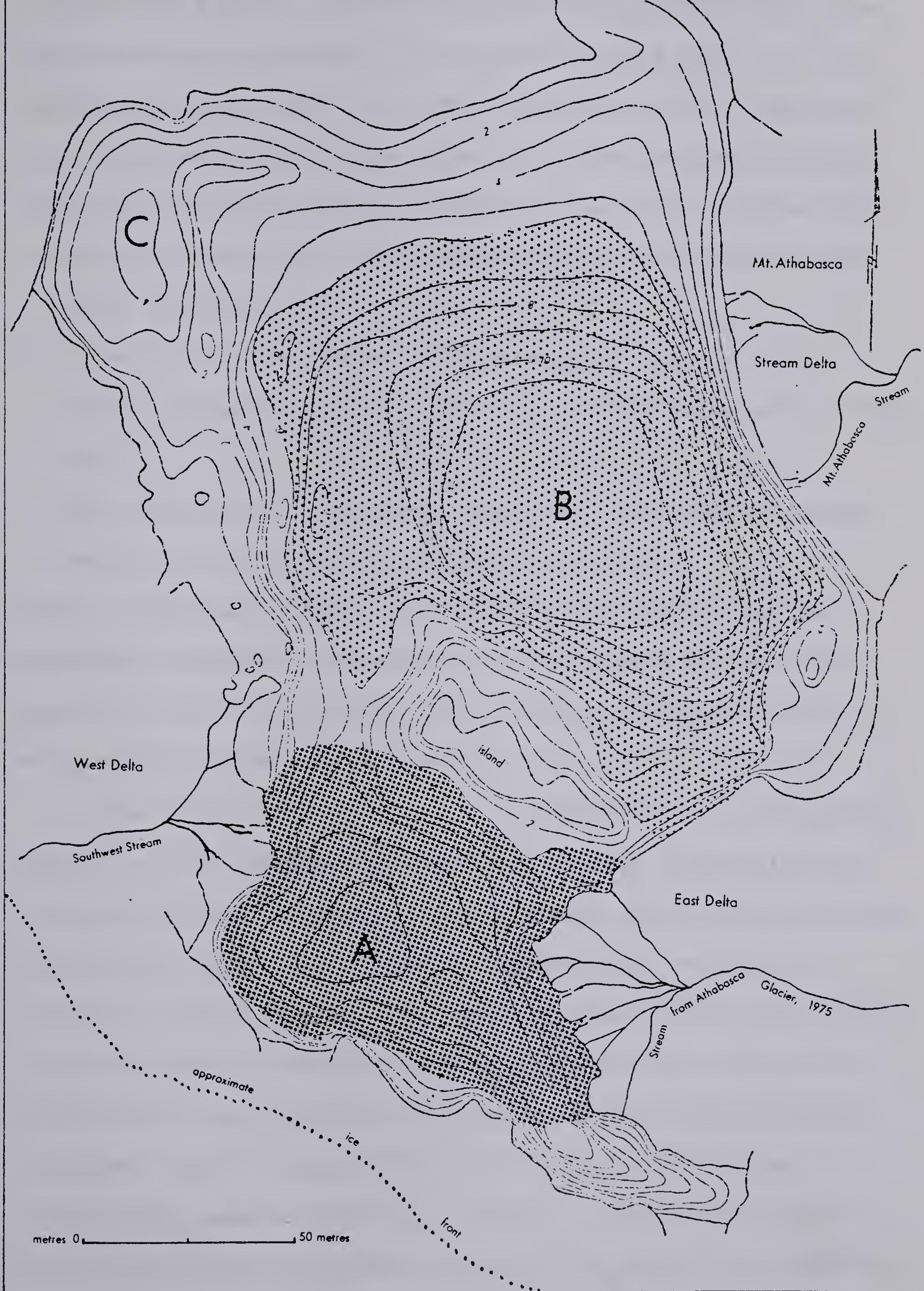
B - ZONE OF MODERATE SEDIMENTATION

C - ZONE OF SLOW SEDIMENTATION

isobath interval : 1m

FIGURE 26

SEDIMENTATION ZONES IN SUNWAPTA LAKE, 1975



field season. Temporary north-trending stream channels resulted in higher sediment accumulation in the Pan 3 area than would have occurred if stream flow had been consistently directed west into the south basin. The Pan 1 site, despite its distance from the major sediment source, may have received greater sediment deposition because of:

1. Current flow from the southeast delta directly to the west channel,
2. Deposition from water, decelerating, and therefore losing capacity, as it left the restricted west channel, and
3. The addition of suspended sediment from the southwest stream to the area (as discussed below).

Zone B, with an area of approximately 0.056km², had an estimated sediment accumulation for the period June 23 - August 21 of 9 - 10 g/cm². Total sediment accumulation was estimated at 5,000 - 5,600 metric tons.

Zone C was the area of slow sedimentation and consisted largely of the distal portion of the lake, the north and northwest section including the site of Pan 4. Most of the north basin above 6m, the west channel, the extreme southeast corner of the lake and the area around the island (up to 6m deep on the north side and up to 3 - 4m on the south side) were included in Zone C. Total area was about 0.068km². The 6m depth in the north basin was chosen arbitrarily because Pan 4 was situated in water around 5m deep. Zone C was shallower south of the island because of

the proximal location of the south basin. Sediment accumulation for Zone C for the period June 23 - August 21 was estimated as 4 - 5 g/cm². Total sediment accumulation for this area may have been 2,700 - 3,400 metric tons.

Total sediment accumulation in Sunwapta Lake for the 1975 field season probably ranged between 11.1×10^3 - 12.8×10^3 metric tons. Stream sediment data show that little sediment was entering the lake prior to July 3. Therefore, the average daily sedimentation rates for the three zones were probably much lower than the lowest rates calculated during the summer. If the average sedimentation rate for Zone A was 0.1 g/cm²/day; for Zone B, 0.01 g/cm²/day; and for Zone C, 0.001 g/cm²/day, the total sediment accumulation in the lake from May 15 to June 20 (when the sediment pans were first placed in the lake) was about 1000 metric tons. Using the average sedimentation rates for the pans in each zone calculated for the last recorded period (approximately August 8 - 21), average daily rates of 0.11 g/cm²/day for Zone A, 0.03 g/cm²/day for Zone B and 0.02 g/cm²/day for Zone C are obtained. (The average daily rate in autumn for Zone C is considered to be lower than that for the last measured period for Pan 4, as given in Table 4A, as this period includes the high discharge and sediment input of August 3 - 8, not included in the last measured period for Pans A - C and 1 - 3, namely, August 8 - 21.) Total sediment accumulation in the lake was approximately 2,407 metric tons for the interval August 21 - October 15. The moderately high

flow peaks occurring after August 21, for example during the warm weather of mid-September, were balanced by the low flow and low sediment input of late September to freeze-up. The resulting mean daily sedimentation rates were, therefore, considered to resemble the lowest mean sedimentation rates recorded in August. From break-up on May 15 to freeze-up about October 15, estimated total sediment accumulation in Sunwapta Lake was in the order of 14.5×10^3 - 16.2×10^3 metric tons.

Several factors make an estimate of total sediment accumulation in Sunwapta Lake in 1975 difficult to obtain. Perhaps the most important factor is the sparse sediment pan coverage which limits the designation of the sedimentation areas. For example, sedimentation in the extreme northeast corner of the lake was probably reduced by the continual movement of water and sediment towards the outlet. The sediment pans were on the lake bed for only two months, albeit what appeared to be the most active period of the melt season in terms of sediment input. Data for the time period prior to June 20 and following August 21 are necessarily based largely on data obtained for July and August, although Sunwapta River discharge records provide guidance for sediment input estimation outside the field season. Additional sediment besides that carried by the southeast stream was introduced by less active streams and perhaps by wave action along the shoreline. Within the lake, redistribution of already deposited material took place as a

result of slumping and erosion by turbidity underflows. Redistribution of sediment was probably toward the pan sites and may have caused overestimation of sedimentation rates. At the same time, the area of each sedimentation zone was probably changed by redistribution. Although the rate of sedimentation was not affected, the total amount of sediment accumulation in areas of slumping and erosion would be greatly reduced. Therefore, it is possible that the sedimentation rates at some sediment pans were inflated by sediment redistribution and perhaps, in the south basin, by mud spilling in over the pan sides; at the same time, this inflated sedimentation rate may have been applied to areas where the actual thickness of deposits did not correspond to the sedimentation rate.

An attempt was made to collect morning and afternoon samples from the southeast stream for suspended sediment analysis, but this was not completely successful. In order to calculate average daily sediment concentration for the stream, missing concentration values were estimated from available discharge and concentration data. Unfortunately, both discharge and sediment load of the southeast stream were extremely variable. Without hourly samples, there was no guarantee that the concentrations calculated from the morning and afternoon samples were the lowest and highest values respectively of the day. Referring once again to streambed erosion, it was not unlikely that periods of maximum discharge corresponded with periods of only moderate

sediment input. This would result in an underestimation of the daily sediment load. It was hoped that, because of the numerous samples taken, any discrepancies would be averaged out over the field season. Daily suspended sediment load calculated for the southeast stream ranged from a low of about 39 metric tons for August 19 to a high of over 1400 metric tons on July 27 (Fig. 23). Periods of high discharge corresponded with periods of high sediment input. For example, from July 3 - 12, the daily suspended sediment load never fell below 450 metric tons; on July 5, 11 and 12, the load was almost twice that amount. This two-week interval was the longest period of exceptionally high sediment input. July 24 - 28 and August 5 were the other two occasions on which daily sediment input exceeded 450 metric tons. For the remainder of July and August, until August 6, the mean daily sediment load was calculated as approximately 193 metric tons. The lowest sediment load values were measured between August 7 and August 21. With few exceptions, suspended sediment load per day was far below 100 metric tons. Based on recorded and estimated values, the total suspended sediment input for the field season (July 2 - August 21) was 16.04×10^3 metric tons. This compares with an estimated sediment accumulation of 11.1×10^3 - 12.8×10^3 metric tons for the period June 23 - August 21. A similar problem to that of estimating sediment accumulation exists when estimating sediment load; no data are available prior to and following the field season. It is reasonable to assume that

sediment input was low between May 15 and July 2. In comparison with the available calculated values, daily sediment load prior to July 2 was probably less than 100 metric tons. An estimated average of 30 - 40 metric tons per day is reasonable, as this compares with estimated sediment loads for days when discharge was relatively low. This gives a total suspended sediment input for this period of 1,400 - 1,900 metric tons. This compares with the approximately 1000 metric tons estimated sediment accumulation in the lake for the period May 15 - June 20. For the remainder of the melt season following August 21, sediment input was probably higher than in early spring since glacier ice melt, and not snow melt, was the meltwater source. However, mean daily discharge in the Sunwapta River after August 21 rarely exceeded 1 cms. Since sediment loads of only 30 - 40 metric tons were calculated for those days in August with low or falling discharge, a similar sediment input estimate of 30 - 40 metric tons seems reasonable for the autumn. This gives a total suspended sediment input of 2,280 - 3,040 metric tons for the period August 22 - October 15. Using August data, an estimated 2,400 metric tons accumulated in the lake from August 22 to October 15.

Estimated total sediment input in Sunwapta Lake from May 15 - October 15 ranged from 19.7×10^3 - 21.0×10^3 metric tons. If one disregards additional sediment introduced by other streams, the difference between total suspended sediment input (19.7×10^3 - 21.0×10^3 metric

tons) and total sediment accumulation (14.5×10^3 - 16.2×10^3 metric tons) was 4,800 - 5,200 metric tons. A daily average of 31 - 34 metric tons of suspended material was transported from the lake by the Sunwapta River. Rough estimates of sediment load carried out of the lake, based on outflow discharge and suspended sediment concentrations from several samples collected near the outlet over the field season give an average of 14 - 25 metric tons per day.

In 1957, from sediment concentration values and sediment pan data, Mathews (1964b) estimated a total daily accumulation of 125 metric tons. This figure is based on data obtained during a period of moderate to relatively high flow in late July (and possibly a period of underflow activity). The daily suspended sediment load carried from the lake was estimated at 4 - 7 metric tons. In 1975, average daily suspended sediment input over the melt season was calculated as 128 - 136 metric tons; average daily sediment accumulation as 94 - 105 metric tons; and average daily sediment output as 31 - 34 metric tons. In comparison, average daily accumulation for the field season, the most active period, was estimated at 179 - 206 metric tons. The larger figures obtained for 1975, excluding the low sediment input of spring and late autumn, can be explained by the greater mean daily discharge and total discharge into Sunwapta Lake, as compared with 1957.

Sunwapta Lake has apparently reached its maximum extent in area. Increased melting of the glacier could result in

flooding of some parts of the deltas and other low-lying areas; however, these sections would probably remain shallow marginal zones of low sedimentation. The lake is, in fact, decreasing in area as the deltas prograde, particularly into the south basin. By late 1976, the east channel had been closed at low water between the east delta and the island. Only the west channel is open for sediment transport into the north basin. These two factors - decreasing area and reduced outlet - should greatly favour even more rapid sedimentation in the south basin than in 1975, as long as major stream flow is directed into the small basin. At the same time, the north basin may be deprived of a large proportion of its sediment input. Infilling of the south basin will be augmented while the existence of the north basin will be prolonged. The opposite would occur if the southeast stream were to flow directly into the north basin. If the southwest stream becomes the major sediment source as it was in 1974, one of two situations could result:

1. Streamflow could continue to be directed into the south basin. Growth of the west delta could encroach on the west channel, limiting this outlet from the south basin, while increased sedimentation and slumping in the proximal zone decreases channel depth. Infilling of the south basin would accelerate.
2. The creation of new stream channels on the west delta could direct flow beyond the west channel into the north basin. This would be a situation analogous to that of

1957 when the southeast stream flowed directly into the north basin. In the new situation, the southwest corner of the large basin would be the proximal zone; most of the deepest section, the zone of intermediate sedimentation; and the northeast corner, the distal zone and the area of low sedimentation. Because of the prevailing northeast movement of water towards the outlet, there would be little sedimentation in the area south of the outlet.

3.5 Factors Affecting Sedimentation in the Lake

During the summer of 1975, several factors affected sedimentation in Sunwapta Lake. The most important of these were:

1. The lake basin geometry and the location of the pan sites,
2. Variations in sediment input,
3. The location of the southeast stream,
4. The influence of streams other than the southeast stream,
5. Slumping,
6. Wind and lake currents, and
7. Ice rafting.

With the retreat of the Athabasca Glacier and subsequent southward migration of the major influent streams, the island and underwater ridges assumed a greater significance in the distribution of sediment throughout the lake. In the summer of 1975, the south basin was the major

recipient of east delta stream sediment. Subsurface flow, and to a lesser extent, surface flow, were restricted by the island. When overflow occurred, sediment was often distributed over the south basin before advancing through the channels into the north basin. Currents moving towards the island were either:

1. Checked, causing a sudden decrease in velocity and subsequent deposition. Material not deposited immediately was deflected along the south side of the island or carried back into the south basin by return flow, or
2. Deflected to the west and east. This allowed for resistance caused by mixing with lake water to effectively reduce current velocity. Deposition in the south basin was therefore favoured.

Concentrations of suspended sediment in the south basin were always higher than in the north basin. This was apparent from differences in water colour between basins and from surface samples of suspended sediment concentration (Fig. 21A). During periods of calm water, much of the sediment distributed throughout the south basin may have had time to settle to a depth greater than 6m (the depth of the west channel). When the lake water was again agitated by increased discharge and winds, this settling layer would not be carried through the shallow channels. The proximal location of the south basin with regard to overflow was enhanced by the island and ridges because the 'normal'

proximal-to-distal distribution of sediment was disrupted. The 9m deep basin contained the movement of underflows and interflows at depth and restricted deposition from these sources to the south basin. This was reflected in the sedimentation rates estimated from sediment pan samples. For every recorded period in 1975, sedimentation rates for the three south basin pans (A, B, and C) were two to three times higher than sedimentation rates for north basin pans (Fig. 24A - 24G). The difference was greater during times of high discharge and suspended sediment concentration when conditions were more conducive to interflow and underflow.

Within the south basin, the steep slopes probably affected the movement of subsurface flows. Interflows and particularly underflows may have been deflected towards one or other of the south basin pans. On June 22/23, July 3/4, and July 25/26, Pans A and C were recovered from the lake bed. Although Pan A was placed nearest the mouth of the southeast stream and at approximately the same depth (within 1 - 2m) as Pan C, the sedimentation rate as calculated in each instance was lower for Pan A than for Pan C which was farthest from the east delta (Fig. 24A and 24C). Particularly at the end of June, the fine material distributed by overflow was apparently spreading out over the south basin; this sediment remained in suspension until the lake water was calm and, therefore, was probably deposited equally at both the Pan A and Pan C sites. The discrepancy in values may be the result of:

1. Differences in times of recovery. However, in each case, the pans were recovered within twenty-four hours of each other.
2. The erosion of sediment, already deposited in Pan A, by high-velocity underflows,
3. Non-deposition because of high-velocity and, therefore, high-capacity underflows. However, Pan A was placed beyond the foreset slopes. It is probable that underflow velocity was reduced on the gentler gradient in the Pan A area; depending on the initial sediment load and the rate and amount of current reduction, deposition would be expected beyond the break-in-slope.
4. Deflection of subsurface flows. At the end of June, the east delta stream was flowing southwest into the lake (Fig. 6). If suspended sediment was being distributed by underflow or interflow, it could have bypassed Pan A. Subsurface flow may have been deflected towards Pan C by the steep slopes to the south; possibly flow was further deflected towards Pan B by the foreset beds of the southwest delta, resulting in higher sedimentation rates for Pan B (Fig. 24B). The situation was reversed when the east delta stream flowed west or northwest into the basin.

Coarse material (sand and coarse silt) was either deposited rapidly as the stream entered the lake or, if transported by underflow, confined to the south basin. Therefore, coarse sediment carried into the south basin was

restricted to that basin.

The north basin generally displayed the expected decrease in rate of sedimentation and amount of sediment deposited towards the distal side of the lake. However, suspended sediment from the southeast stream was distributed to the north basin via the west and east channels; variations in sedimentation rates, particularly among the channel and centre basin pans (Pans 1, 2, and 3), showed the effects of the island on surface and subsurface flows. Generally, only sediment in the surface 5 - 6m was carried through the west channel. In the east channel, sediment movement was restricted to overflow and interflow at less than 3m. Underflows have been observed travelling up low-angle reverse slopes but this was prevented in the south basin by the steepness of the channel ridge. On reaching the north basin, current velocity gradually declined and deposition increased. Sediment accumulation on the ridges was limited by the steep slope gradient. Any material moving downslope due to slumping or underflow would gravitate towards the deep flat-floored section of the basin. With the exception of Period 3 (and perhaps Period 4) sedimentation rates for Pan 2 were double the rates at Pan 3. For Periods 3 and 4, rates at Pan 2 were higher than those at Pan 1 (Fig. 24D - 24F)

Beyond the channels, surface sediment did not spread laterally to any great extent because of:

1. The momentum of northward-flowing water moving through

the channels towards the outlet, and

2. The prevailing wind direction.

Overflows, 'split' by the island, eventually converged in the vicinity of Pan 2. This may have kept surface concentrations in the area high in proportion to the Pan 1 and Pan 3 sites (Fig. 21A), particularly during periods of overflow. Sedimentation rates at Pan 2 were probably increased by this convergence. The effect of basin geometry on sediment distribution was enhanced by changes in the southeast stream. During high flow stages, the east delta downstream of the parking lot was often submerged. This occurred at the beginning of July and again at the end of July/beginning of August. During and after these periods of 'flooding', changes occurred in the location and relative importance of several of the stream channels. The effects of these changes were apparent in both the south and north basins. When the southeast stream flowed southwest into the lake, material may have bypassed Pan A. Even if subsurface flow had been deflected back towards Pan A, most of the coarser material was already deposited; flow velocity was checked by impact with a steep slope or reduced with reduced slope gradient in the deeper section of the basin. When stream flow was directly west towards Pan A, as it was at the end of July, the sedimentation rate for this pan was the highest recorded for all the pans (Fig. 24A - 24G). At this time, any suspended sediment transported by underflows and interflows was carried towards Pan A and the centre of the

south basin. Beyond the steep foreset beds of the east delta, velocity was reduced and deposition from subsurface flows augmented.

Sedimentation rates for either the south or the north basin only suggest underflow activity; they cannot provide absolute proof. The very high rates in the south basin relative to rates estimated for the north basin pans are a good indication of subsurface flow, taking into account the effects of the island and channel ridges. For example, Pan 3, which was about as far from the east delta as was Pan C, did not show a sedimentation rate more than half that of the south basin pan. It is possible that underflow occurred in the north basin but the major input of water and sediment was always directly into the south basin. It is not possible to ascertain positively whether an underflow actually passed over a pan. One would have to know whether the underflow was eroding or depositing, of high or low density (that is, whether or not sand was carried in suspension), whether a traction carpet was present, and the area where deposition from the current began. A high sedimentation rate could reflect deposition from one or more underflows; conversely, a low rate could result from erosion or entrainment of previous deposits by the passage of an underflow of high velocity. Sedimentation rates are based only on material present in the pan on recovery.

The momentum provided by high discharge at the end of July also directed overflow sediment west towards Pans A, B,

and C. Material was then carried northwards through the west channel rather than back towards the south end of the lake. When discharge was high and stream flow west or northwest into the south basin, there was less opportunity for distribution of sediment over the smaller basin. With less time to settle in the south basin, it is likely that a greater proportion of sediment was carried more rapidly into the north basin than when discharge was low or stream flow southwest into the lake. This probably accounts for the wider fluctuations at the Pan 1 site, during periods of high discharge, than in other areas of the north basin (Fig. 21A).

Throughout the field season, a major portion of the east delta stream water flowed west into the south basin. However, several other stream channels gained temporary importance. In mid-July, a channel incised on the delta directed stream flow northwest towards the east tip of the island. This flow was split by the island, some water moving into the north basin and the major portion flowing immediately south of the island towards the west channel. Although suspended sediment concentration in the lake was always high (relative to most non-glacial and many glacial lakes), the movement of sediment-laden water south of the island, around the west tip and into the north basin was easily distinquished by colour. Overflow sediment from this stream channel, aided by the general northward flow of lake water, was swiftly transported out of the south basin.

The current flowing into the north basin moved west along the north side of the island before being assimilated in the general movement towards the outlet. This was apparent from observation and from drogue movements (see Fig. 12). Pan 3 was bypassed. If subsurface flow occurred, any interflows or underflows were probably directed away from Pan 3 because of initial current momentum and slope gradient. This stream current (northwest) was less effective in distributing suspended sediment towards the Pan 3 site than were the stream branches flowing due north into the large basin. Several such channels were established on the east delta during periods of high discharge. In the first week of July, a branch of the stream flowed north; at this time however, although sediment concentrations were high, any effect on Pan 3 was overshadowed by the large proportion of sediment directed towards the south basin and Pans 1 and 2. When stream discharge into the south basin was reduced, the distribution of sediment by a north-trending channel assumed greater significance. Pan 3 was directly in the path of sediment movement by overflow, interflow and underflow, the latter perhaps originating as slumps and debris flows on the east ridge. This may account for the higher sedimentation rate at Pan 3 than at Pan 1 or 2 for Period 3 (July 14 - 25), (see Table 4A and 4B). By July 30, the channel was well-established. On July 29, the second Pan 3A disappeared. On August 1, it was discovered that Pan 3 had been disturbed prior to recovery. At this time, surface

concentrations of suspended sediment near Pan 3 were similar to, and occasionally exceeded, concentrations at Pan 1 (Fig. 21A: July 21, 22, 28 and 29). Although sediment input from the smaller north channel was less than that from the west-trending channels, the distance between Pan 3 and its sediment source was far less than the distance between Pan 1 and its source. Furthermore, there was a reduction in velocity as subsurface flow, beyond the shallow lake margins, passed from the steep delta slope to an area of gentler slope gradient south of Pan 3. When the north-flowing streams were active, the sedimentation rate at Pan 3 exceeded the rates of the other north basin pans. As discussed above, this may relate to either underflows arising from density differences with increased direct sediment input, or to slump-generated underflows resulting from rapid deposition on a high-angle slope. After the first week in August, these channels were inactive. For Periods 5 (August 4 - 8) and 6 (August 9 - 21), the sedimentation rate at Pan 3 was less than that at Pan 2 and only one-half to one-fourth that of Pan 1 (see Table 4A and 4B).

Since Pan 2 was closer to the east channel, its sedimentation rates may have been influenced by the north-trending stream channels during Periods 3 and 4; during this time, Pan 2 sedimentation rates were higher than those at Pan 1. Otherwise, changes in channel location had little effect on Pans 2 and 4. Pan 4, at the distal end of the lake, was affected by the overall direction of lake

water movement rather than by specific currents originating from the east delta.

The addition of water to the lake by streams other than the southeast stream is indicated by the discrepancy between outlet and southeast stream mean daily discharge during high flow periods (Fig. 17 and 18). Some suspended sediment was introduced into Sunwapta Lake by the southwest stream, especially during periods of warm weather and high discharge. Several integrated samples collected in July showed stream concentrations ranging from 116 mg/l to 1894 mg/l. The latter concentration occurred during the hot weather of Period 2 (July 7 - 17). At this time, discharge was the highest, and the differences between discharge in the southeast stream and that of the outlet one of the largest recorded in the summer. Similarly, the Mt. Athabasca stream was relatively inactive except during periods of high melt. Both streams probably influenced sediment distribution and accumulation in the lake directly by the additional supply of sediment and indirectly by 1) slumping and slump-generated underflows along the deltas and 2) influencing water movement within the lake. Convergence of east-flowing water from the west delta with west-flowing water from the east delta probably increased deposition in the south basin. Water flowing northeast from the west delta transported sediment directly through the west channel into the larger basin. Overflow and interflow sediment from the Mt. Athabasca stream was generally carried directly to the

outlet by the northward movement of lake water.

Minor factors affecting sedimentation include wind and lake currents and ice rafting. At Sunwapta Lake, the colder, heavier air above Athabasca Glacier flowed down the slope of the ice surface and beyond the toe to replace the warmer air above the ground and lake. The winds increased in duration and intensity with increased air temperatures. Periods of warm weather were usually accompanied by high sediment input. Not only did sediment concentration increase (with greater particle-to-particle interaction) but wind-generated turbulence helped keep sediment in suspension for greater lengths of time.

Work carried out in the summer of 1974 (Gilbert, 1975a) indicated that the katabatic wind influenced both surface and bottom movement of water. When wind force was high, water in the south basin was piled against the island, and forced towards and through the channels.

The overall direction of lake water movement in Sunwapta Lake was northeast towards the outlet. Therefore, sediment carried into the lake by overflow and interflow, and no longer influenced by the initial direction of current flow, was distributed in a northward direction from the south basin through the channels into the north basin (see Figure 12). In spite of this predominant movement of lake water, the northwest corner of the lake was not a 'backwater' in terms of suspended sediment distribution. Sediment plumes were observed moving northeast from the west

channel, but there was little difference between surface sediment concentrations near Pan 4 and those in the outlet (Fig. 21A). The prevailing south wind propagated waves towards the north shore and the site of Pan 4; more sediment was transported to the distal end of the lake than would have been possible had the lake been calm. During the first week in August, suspended sediment concentrations at Pan 4 and in the outlet were disproportionately high relative to concentrations at other pan sites. On the afternoon of August 3 the concentration at Pan 4 exceeded that near Pans 2 and 3 (Fig. 21A). This was a period of unsettled weather with wind and rain (rain also agitated the lake water surface). It is likely that strong winds hastened the spreading of sediment by overflow. Since Pan 4 surface samples were collected at the same time as other pan site samples in the lake, the high sediment concentrations at Pan 4 may have resulted from a previous influx of sediment that no longer affected the southern part of the lake. Pans 2 and 3 may have already been influenced by the low sediment input of the following morning and by the westward direction of current flow from the east delta towards Pans B and 1. A similar situation existed during the hot windy weather of July 26 and 27.

The katabatic wind, therefore, served a two-fold purpose in sediment distribution:

1. It aided in keeping sediment in suspension because of wind-induced turbulence, and

2. It hastened and extended the distribution of overflow and some interflow sediment towards the distal end of the lake.

The sedimentation rate at Pan 4 for July 6 - 17, with hot windy weather, high discharge and large sediment input, was over 0.15 g/cm²/day (see Table 4A and 4B). This also reflects the influence of water moving through the west channel. At no time during the 1975 field season was the sedimentation rate measured at Pan 4 as low as the rates estimated by Mathews (1964b) in the northwest corner for July 21 - 23, 1957. Rates for his Pan 5 and Pan 6 were 0.001 g/cm²/day and 0.015 g/cm²/day respectively. At that time, stream flow was from the southeast directly into the north basin. Both wind and water movement combined to transport suspended sediment away from the northwest corner and directly towards the outlet.

Ice rafting played a minor role in sediment distribution in Sunwapta Lake. Pieces of ice were occasionally carried into the lake by the southeast stream. Since this was glacier ice, it no doubt contained sediment. However, the effects of this sediment were negligible. On the night of August 11/12, ice formed over much of the lake surface. Ice rafting of numerous stones, some several centimetres in diameter, was observed. In this manner, a small number of pebbles and some very coarse material which would normally be found only on the deltas was distributed throughout the lake.

3.6 Factors Affecting Measurement of Sedimentation Rates

Both field work and laboratory experiments are hampered by human and mechanical error, but the former is further affected by unpredictable, often adverse field conditions. The location of Sunwapta Lake adjacent to the Athabasca Glacier, while creating an interesting environment for study of proglacial lacustrine sedimentation, at the same time seriously affected field work carried out in the lake during 1975. This was particularly true with reference to the sediment pans. These pans were awkward and heavy, and could only be brought up when the lake was calm. Because of katabatic winds, calm periods were infrequent and of short duration. Wind and waves occasionally resulted in the loss of some sediment while a pan was being recovered and emptied. The boat was unstable and each pan was taken to shore before being emptied. All seven sediment pans, plus the small cake pans, could not be recovered and replaced on the same day. Pans were usually brought up over an interval of two to three days. Therefore, while the effects of an influx of sediment or turbidity underflow may have influenced the sedimentation rate measured at one pan for a particular time interval, the rate of another pan recovered immediately prior to the influx or underflow may show the effects during the following interval. The sedimentation rates calculated may reveal a larger or smaller discrepancy between pan sites than actually existed. This was particularly true for the south basin, and for the north

basin when conditions were favourable for slumping or turbidity underflow activity.

An echo sounder was used during placement of the sediment pans on the lake bed. Steep slopes likely to be subject to slumping were avoided. During each successive recovery, a marker float indicated the location of the pan site for replacement. However, it was impossible to reinstate a pan exactly and it is likely that some pans were put back on a slope which subsequently influenced the sedimentation rate through slumping or underflow activity. In the east channel, for example, the slope was found to drop sharply immediately north of the Pan 3 site. This was discovered during an attempt to replace Pan 3.

Disturbance of the pans also affected the calculation of sedimentation rates. Depending on the location and weather conditions, pans could be subject to disturbance by:

1. Slumping. A series of slumps on the north face of the east channel ridge probably explains the tilting of Pan 3 and the disappearance of the two Pan 3A's.
2. High-velocity flows. Density underflows may have caused actual movement of a pan, or erosion of sediment already deposited in the pan, resulting in an underestimation of the sedimentation rate.
3. Wind, waves and currents. The force of high winds, waves and currents from the streams against the pan floats may have resulted in the pans being dragged along the lake bed, with consequent disturbance of bottom and settling

sediment.

4. Ice. On the morning of August 12, Pan 2A was observed being dragged by the break-up and northward movement of ice. It was impossible to determine whether any of the other pans were similarly affected. Furthermore, pan disturbance by drifting ice may have occurred on other, unobserved, occasions.
5. Spillage of fine unconsolidated bottom sediment over the pan sides as the pans were being replaced on the lake bed (Mathews, 1964b).

Any or all of these factors could have resulted in an estimated sedimentation rate far below or in excess of the actual sedimentation rate at a particular site. Pans 4 and 4A at the distal end of the lake, in an area of gentle slopes and relatively slow deposition, were the least likely of the sediment and cake pans to be disturbed.

Adverse weather also affected collection of suspended sediment samples. An attempt was made to take daily morning and afternoon samples for surface suspended and dissolved sediment concentration, but frequently this could be done only for the east delta stream. On several days, surface sampling could not be carried out in the lake at all. The lack of data for certain periods and variations in times of sampling, like the variations in times of sediment pan recovery, influence the interpretation of sediment distribution and deposition within the lake. To what extent this occurs can only be roughly estimated. Subsurface

sampling with the Van Dorn bottle sampler was adversely affected by the boat drifting during sampling. Depending on the force of the wind and resulting waves, subsurface concentration profiles were not vertical from surface to bed; each sample taken was collected somewhat further north than the previous sample.

4. Sedimentary Structures in the Sunwapta Lake Cores

4.1 General

Primary sedimentary structures are those structures, such as bedding and laminations, formed "... at the time of deposition or shortly thereafter and before consolidation of the rock in which they are found" (Pettijohn and Potter, 1964). Such structures range from isolated microscopic features to large-scale sedimentation units. A sedimentation unit is defined in Pettijohn and Potter (1964) as "... a layer or deposit formed under conditions of essentially constant flow and sediment discharge; distinguished from like units by changes in grain-size and/or fabric indicating changes in velocity and/or direction of flow." Beds are considered to be sediment layers or strata "... distinguished from one another by lithological changes" (Selley, 1976). Bedding is defined by Selley (1976) as "... layering within beds on a scale of 1 or 2cm" and lamination as "... layering within beds on a scale of 1 or 2mm". Common usage divides sediment layers into strata greater than 1cm in thickness, and laminae, less than 1cm in thickness.

Laboratory experiments and field observations strongly suggest a close correspondence between sedimentary structures and the environment in which they were formed (Antevs, 1931 and 1951; Kuenen, 1950 and 1951; Kuenen and Migliorini, 1950; Kuenen and Menard, 1952; Carozzi, 1957;

McKee, 1957; Sanders, 1963; Briggs and Middleton, 1965; Middleton, 1965 and 1966a - 1966c; Walker, 1967; Chipping, 1972; Hampton, 1972; Middleton and Hampton, 1973; Ashley, 1975; Shaw, 1975; Selley, 1976). Changes in velocity may produce variations within a structure or an entirely different structure or sedimentation unit. Furthermore, changes within a structure, such as in thickness, degree of distortion, grain-size, or arrangement and number of internal components, or changes in the arrangement and vertical thickness or horizontal extent of one or more sedimentary units indicate gradual or abrupt variations in the environment through time and space. This has been discussed, for example, with respect to varves (Antevs, 1931 and 1951; Kuenen, 1951), turbidites (Kuenen and Migliorini, 1950; Kuenen, 1951; Walker, 1967), and stratification and bedforms (Harms and Fahnestock, 1965). (For a review of experimental work on primary sedimentary structures, to 1965, see Brush, 1965.)

The seasonal and highly variable nature of sediment input associated with many glacial and proglacial lakes gives rise to a number of primary sedimentary structures; some of these, in particular varves, have become almost synonymous with glaciolacustrine deposits. The more common glaciolacustrine sedimentary structures may be subdivided into three classes:

1. Rhythmic sedimentation units, representing annual, daily or intermediate fluctuations in sediment input,

2. Isolated sedimentation units or structures, in particular, those associated with turbidity underflows, and
3. Post-depositional deformation structures:
   a. large-scale disturbed sequences, and
   b. distorted or contorted lamination.

4.1.1 Rhythmic Sedimentation Units

One of the outstanding features of many glacial lake deposits is the alternating beds of fine-grained and coarse (or coarser)-grained sediment forming rhythmic sedimentation units. Where such rhythmic units are considered to be annual deposits, the result of relatively high sediment input during the melt season and relatively low sediment input during the winter (between freeze-up and break-up), they have been termed varves (Antevs, 1931 and 1951; Kuenen, 1951; Agterberg and Banerjee, 1969). A 'simple' varve consists of a dark, predominantly clay, winter layer and a light, predominantly silt, summer layer (see, for example, Pettijohn and Potter, 1964, Plate 1). The beds may appear to be massive, that is, without visible internal structure (Pettijohn and Potter, 1964) or graded, that is, showing "... gradation in grain-size from coarse below to fine above" (Middleton, 1965). Massive beds occur when the sediment introduced is of one size, or settling out of material takes place in water not calm enough to allow slow steady settlement according to the actual fall velocity of each particle. Grading reflects the settlement of different

sized particles according to their fall velocity. If slumping or minor introduction of sediment occurs after freeze-up, the winter varve layer might show one or more laminae and possibly slump structures. The fine-grained beds should be of approximately equal thickness throughout a glacial lake except where steep slopes prevent a thick accumulation of sediment. By contrast, the summer silt layer shows a decrease in thickness, and a decrease in predominant grain-size, with increasing distance from the sediment source.

In a 'composite' varve (Duff, Hallum and Walton, 1967), the coarse summer layer is subdivided into thinner beds and laminations. These internal structures are generally considered to reflect short-term changes in the environment such as fluctuations in sediment input or variations in current velocity. For example, where glacial melt is the dominant source of sediment, diurnal fluctuations in sediment input may produce thin parallel laminations (Kuenen, 1951; Mathews, 1964b; Duff et al., 1967). The fine-grained laminae represent the settling out of material in relatively calm water in the late night /early morning period; the somewhat coarser sediment (which may include sand) represents material deposited by overflows, interflows and underflows, almost immediately after the afternoon influx of sediment. A period of warm sunny days and cool calm nights may produce parallel laminations forming 'miniature' rhythmic sedimentation units. On a larger scale,

variations in grain-size may form 'sets' of parallel laminae. Alternating periods of warm and cool weather may produce rhythmic sedimentation units, in which sets of parallel laminations (and other sedimentary structures) reflect the greater ice melt and higher sediment input associated with high temperatures. Periods of cool weather, with low sediment input and little difference between daytime and night time temperatures, may be marked by sets of relatively faint laminations, or fine-grained massive or graded beds. Such larger sedimentation units may appear as 'psuedo varves'. Where the winter varve layer is absent or obscured, these 'psuedo varves' may be mistaken for annual deposits. The thickness of each individual lamina or bed within a sedimentation unit present in a core depends on the amount of sediment deposited in the core location and the length of time in which conditions of weather, melt, discharge, sediment input and other environmental factors remained constant.

Parallel lamination, massive beds and graded beds may also be associated with turbidity underflows, as discussed below.

4.1.2 Sedimentary Structures Associated with Turbidity Underflows

Glaciolacustrine deposits may also contain beds and bedding sequences attributed to turbidity underflow activity (Kuenen and Migliorini, 1950; Kuenen, 1951; Kuenen and

Menard, 1952; Middleton, 1965 and 1966c; Chipping, 1972; Middleton and Hampton, 1973). The 'ideal' turbidite sequence has been described by Bouma (1962) and analysed by Simons et al. (1965). Briefly, the sequence from base to top consists of a coarse-grained massive or graded bed, overlain by a laminated bed of sand, a bed of cross-laminated sand, a bed of laminated sand and silt, and finally by a bed of laminated mud representing settlement of fine material from the 'tail' of the underflow. The beds forming this sedimentation unit on a point on the lake bed are an indication of the current velocity decay through time, at that particular point. Once an underflow reaches slopes of lower angle, 'freezing' of the traction load, material moved along the bed by rolling and saltation (Sanders, 1965; Selley, 1976), may take place. Here, one might expect to find a 'Bouma-type' sequence. The 'frozen' traction carpet forms the massive, coarse-grained bed. Increased bed roughness causes drag on the adjacent still-moving current, and sand in suspension is deposited as parallel laminae. With the loss of much of its coarse sediment load, current velocity is reduced; ripples form on the sand bed (climbing ripples, if sand fallout is still taking place); current velocity is further reduced by resistance provided by bedform roughness; and silt and the sand remaining in suspension is deposited as parallel laminations. Eventually, only mud is left to settle out. The absence of a complete 'Bouma-type' turbidite sequence at a site does not mean an

alternate explanation, other than turbidity underflow activity, must be found for the formation of the sequence. Not all turbidity underflows transport material in a traction carpet (Sanders, 1965); the total load of the current may be carried in suspension. Deposition of the traction load and of the suspension load produces different structures within a turbidite sedimentation unit and this has led to discussion of what actually constitutes a turbidity underflow and its deposits (see Sanders, 1965). If a traction carpet is absent, the base of the sedimentary sequence may consist of laminated or cross-laminated sand. If a traction carpet is present (in the form of a debris flow or inertia flow), but sand is not carried in suspension, the resulting deposits may consist of a coarse, structureless bed, a bed of ripple cross-lamination and a layer of laminated silt and clay. Turbidity underflows not transporting sand in suspension are termed low-density underflows. Lacking both a traction carpet and sand in suspension, an underflow may leave its mark in the form of a tooled or scoured bedding surface, laminated silt beds and distorted and convoluted fine-grained laminae. A turbidity current originating on a very steep slope may have sufficient velocity to erode, rather than deposit, material. Only fine-grained sediment from the tail may eventually settle out in areas of erosion.

Velocity decay and changes in sediment load occur, not only with time but in space, from the original inception of

the underflow to its eventual dissipation somewhere on the lake bed. With increasing distance from the sediment source, the lower intervals of the turbidite sequence (the massive and coarse-grained, graded beds and the lower interval of parallel lamination - see Bouma, 1962, and Walker, 1967) will not be present. This reflects current velocity decay through space, from the upper flow regime through the lower flow regime to relatively calm water, as well as the sediment deposition that has already occurred. Walker (1967) has analysed turbidite sequences in terms of number and thickness of intervals present. He suggests that the absence of the lower sediment intervals is a factor of the distance of the sample from the sediment source. A sequence beginning with current ripple cross-lamination is a good indication that current velocity at this point had already decreased to the upper part of the lower flow regime (Bouma, 1962; Simons et al., 1965; Walker, 1967). If the current dissipates before it reaches a barrier or the distal end of the lake basin, only fine-grained material will be left to settle out from suspension. Deposits should consist of fine silt and clay, rather than sand and coarse silt, or a combination of coarse and fine sediment. The presence of syndepositional deformation features suggests that current movement was still taking place. Fine-grained, graded beds may be the deposits of an underflow tail.

Turbidity underflows generated in flume experiments are checked at the end of the flume. Sediment settles out from

suspension forming a bed grading upwards from coarse sand (if present) to clay. In a lake or reservoir, an underflow may be checked by a natural or man-made obstacle before the current can dissipate. Although a coarse-grained massive or graded bed could be present, the resulting turbidite sequence at this point would lack the parallel laminations and cross-laminations of the 'Bouma-type' turbidite sequence.

Cross-lamination (and, at a larger scale, cross-bedding) is a common feature in turbidite sequences. Current ripple cross-lamination is the cross-sectional expression of the moulding of bed material into ripples by currents in the lower flow regime (Simons et al., 1965; McKee, 1965). Stoss-side erosion and lee-side deposition cause lateral and vertical migration of ripples, which in turn produces cross-laminated beds (McKee, 1965; Selley, 1976). A cross-laminated bed generally blends upwards into horizontal lamination; this reflects a decrease in current velocity with increased bed roughness and deposition of the remaining coarse sediment load. Furthermore, as velocity decreases, the 'necessity' of resistance due to bedform roughness decreases. The ripples become more and more elongated with increasing wave length. Eventually, the ripple cross-lamination may disappear into wavy or horizontal parallel laminae. In a lacustrine environment, ripples at depth are generally associated with turbidity underflow because of the current velocity required along the

bed, and the fact that ripples can only form in sand. An extensive study of ripple cross-lamination was undertaken by McKee (1965).

Velocity decay should be evident both vertically and laterally from the source. However, if an underflow travels in 'pulses' or is followed immediately by another underflow, disturbance and erosion of the initial deposits may occur. Fine-grained material may be eroded by the head of a subsequent underflow, or existing bedding surfaces may be deformed, and silt and fine sand incorporated in the overlying coarse deposits. Horizontal laminations may be folded into anticlines and synclines, or recumbent folds. Inversely graded or multi-graded coarse-grained beds may be produced.

4.1.3 Post-depositional Deformation Structures

After a structure has been formed, it may be subjected to stresses that deform, and sometimes obliterate, the structure. Such deformation may be on a very minor scale, affecting only one set of laminae, or it may be on a very large scale, affecting several varves, or beds many metres in thickness. (A brief summary of common post-depositional deformation structures is given in Selley, 1976). Among the most common deformation structures recognized are slumps and slides, distorted or contorted beds and laminations, and load structures. Slumps and slides frequently cause folding and faulting of laminae and beds. By contrast, liquefaction

and grain-flow generally destroy any primary depositional structures present. Between these two extremes, one may find slump bedding containing sediment clasts, flow structures and fragments of graded beds, horizontal and cross-lamination, and other depositional features. Slump bedding may lie unconformably over undeformed bedding or it may deform the bedding surface over which it moves. The stress caused by a swiftly-moving grain-flow or slide on a fine-grained, non-cohesive bedding surface may deform the underlying sediment. As with ripples, the deformed sediment may increase resistance to flow because of greater 'bedform roughness', thereby slowing flow velocity. Alternatively, a low-velocity, coarse-grained slump or slide may exert sufficient pressure on underlying fine-grained sediment to cause deformation by differential loading.

Turbidity underflows can be generated by slumps and slides (Middleton and Hampton, 1973). Therefore, slump deposits at one site may correlate with underflow deposits at another site. A sedimentation unit deposited by a high-velocity, slump-generated underflow may be overridden, perhaps disturbed, by the slow-moving slump material.

Distorted bedding or lamination may result from other factors besides slumps. Distorted lamination in coarse and/or fine-grained sediment has been related to:

> "... 1) an overriding force ... [such as the passage of turbidity currents], 2) differential overloading, and 3) slow mass movement of saturated sediments on an inclined

slope" (Coleman and Gagliano, 1965; see also, Dzulynski and Smith, 1963).

Convolute lamination, in which the laminae have been deformed into anticlines and synclines, has been discussed by Dzulynski and Smith (1963); Sanders (1965); Coleman and Gagliano (1965); and Selley (1976), among others. Selley (1976) suggests that convolute lamination "... probably originates ... by the dewatering of sediment aided by the shear stresses set up by the turbidity flow itself ..." Differences in degree of porosity and cohesiveness between sand and fine-grained laminae create stresses within the sediment layers that may cause "... lengthening of the laminae without any lateral shortening" (Dzulynski and Smith, 1963); that is, the formation of anticlines and synclines which, unlike the folds created by slumping, are not reduced in areal extent. Sanders (1965) has included convolute laminae in the group of sedimentary structures considered to have been produced during deposition from turbulent suspension. This could lead to discussion as to whether convolute lamination is a syndepositional or a post-depositional deformation structure. If several mechanisms are responsible for the formation of convolute laminae, then the classification of the convolutions as to syndepositional or post-depositional may depend on its sedimentary context.

Perhaps an unusually rapid and relatively heavy deposition of fine-grained material, for example, deposition

from the tail of a turbidity underflow in an area of otherwise slow settlement of silt and clay from overflows, could generate increased pore water pressure within the sediment. Gradual expulsion of water from the underlying silt could possibly result in small-scale, fine-grained convolute laminae within fine-grained sedimentation units. Compaction due to the weight of overlying sediment may further deform convolute laminations by flattening out the anticlines and synclines against the upper and lower bedding surfaces (Grabau, 1960). Differential loading may also result in the formation of load casts and pseudonodules (Selley, 1976). Whereas convolute lamination refers to a set of laminae deformed into anticlines and synclines, load casts deform the underlying sediment from above only. Load casts disrupt otherwise horizontal fine-grained lamination. It is possible for segments of the overlying coarse-grained bed to become completely detached from the bed and surrounded by distorted laminae or structureless mud in a massive fine-grained bed; these segments are frequently termed pseudonodules (Pettijohn and Potter, 1964; Selley, 1976).

The primary sedimentary structures discussed above are those which are likely to be present in a section of glaciolacustrine deposits. The types of structures, their development, thickness and location within the section (or core) can indicate the location of the section in the lake relative to the sediment source, and the changes in the

environment in which the sediments were deposited.

4.2 The Sunwapta Lake Cores: Primary Sedimentary Structures

4.2.1 General

On July 30 and 31,1975, seven cores were obtained from Sunwapta Lake, four from the north basin and three from the south basin (Fig. 6) using a gravity corer. The unconsolidated, predominantly fine-grained nature of the lake bed sediments caused problems in the coring operation. Several cores were lost completely, flowing out of the corer as it was taken from the water. Of the cores that were successfully collected, there was some disturbance and loss at the base of the cores on removing and sealing the core liner. Horizontal lamination at the base of several cores shows faulting and other disturbance probably related to the flowage of unconsolidated mud before the cap was put on the core liner. As the corer descended through the bottom deposits, frictional resistance between the core liner and the sediment caused drag along the sides; laminae were either bent downwards at the sides, or assumed a convex-upward cross-sectional profile. The degree of convexity varies from core to core and within each core. Several of the cores also show slight, 1 - 2mm, vertical displacement within sets of laminae. This faulting may be due to drying. A more serious problem than the above is the loss of small sections of several cores which broke off or crumbled away, leaving gaps in the core 'record'.

Despite some disturbance and loss, it was thought that primary sedimentary structures visible in the cores could be related to sedimentary processes and rates of sedimentation operating in Sunwapta Lake within recent years.

4.2.2 Sedimentary Structures in the Cores

Several primary sedimentary structures can be recognized in some or all of the cores. The predominant features, defined largely on the basis of descriptions and photographs of similar features found in Pettijohn and Potter (1964), Middleton (1965), Jopling and MacDonald (1975), and Selley (1976), can be classified as follows:

1. Large-scale (several centimetres thick) rhythmic sedimentation units,
2. Horizontal laminations,
3. Coarse-grained structureless beds,
4. Current ripple cross-lamination,
5. Post-depositional, deformation structures:
    a. large-scale disturbed sequences, and
    b. distorted or contorted lamination.

These features are not necessarily mutually exclusive. Two or more adjacent structures may form a larger sedimentation unit.

4.2.2.1 Large-scale Rhythmic Sedimentation Units

This is a prominent feature of all seven cores. All other structures except certain deformation structures and

some structureless sand beds are contained within the cyclic sedimentation units. Each unit consists of:

1. An apparently structureless or faintly laminated fine-grained bed, and
2. A complex bed consisting of fine-grained, or both fine-grained and coarse-grained sediment, generally in horizontal laminae, but also containing graded bedding, coarse-grained structureless beds, contorted and otherwise disturbed lamination, and ripple cross-lamination.

The division between units and between beds within each unit is not sharply defined; rather, it is marked by a gradual change in the number and grain-size, and frequently in the thickness, of the horizontal lamination. The measurement of each unit size is somewhat arbitrary because of the absence of distinct boundaries. Unit size is variable from core to core and within each core.

4.2.2.2 Horizontal Lamination

The most common and perhaps the most distinctive, feature of all seven cores, horizontal lamination occurs throughout the length of each core. The laminae tend to be concentrated in sets and are better developed and more numerous in the complex bed of the rhythmic sedimentation units. Where coarse material is present, the laminae are more distinct and the sets larger (that is, thicker). There are several beds of laminated sand, and sets of laminae

consisting of sand and silt. Otherwise, lamination is caused by alternating laminae of clay and fine silt, or by variations in colour. The indistinct nature of individual fine-grained laminae may make laminations appear thicker in predominantly fine-grained sediment.

4.2.2.3 Coarse-grained Structureless and Poorly Laminated Beds and Bedding

Coarse-grained structureless beds and bedding is present in several cores, ranging in thickness from several millimetres (almost a very thick lamina) to several centimetres. The coarsest beds consist of well-sorted sand. There are also beds of unsorted coarse silt and medium to fine sand. These structureless sedimentary features are not isolated beds, but tend to occur adjacent to similar beds of slightly different grain-size (graded bedding), or in bedding sequences separated by finer-grained bedding or laminae.

4.2.2.4 Ripple Cross-lamination

Ripple cross-lamination is rare, clearly visible in only one of the seven cores. A sequence of what may be a section of cross-laminated fine sand viewed normally or tangentially to current flow direction is also present in one core. In general, the cross-laminated sequences grade upwards into horizontal lamination.

4.2.2.5 Post-depositional Deformation Structures

Sections of several of the cores have been folded and faulted due to subaqueous slump activity. Individual beds and laminae have been contorted or broken into fragments that preserve the original structural features. Sediment clasts of both coarse- and fine-grained material have been incorporated into the disturbed bedding.

The deformation in all cases has apparently affected more than one rhythmic sedimentation unit. With one exception, there is no sharp lower boundary between the slumped material and the subjacent undisturbed material; the degree of deformation decreases with sediment depth. Laminations and strata have been folded into anticlines and recumbent folds.

Two cores (1 and 7) show well-developed load casts and pseudonodules. Segments of structureless sand beds protrude into underlying fine-grained laminated or structureless beds, causing slight upfolding of surrounding laminae or bedding sequences. In one core, a portion of the overlying sand bed has become completely enclosed in the subjacent fine-grained sediment.

On a smaller scale (less than 1cm), fine-grained single laminae or sets of laminations have been folded, stretched or interlaminated. Several examples are visible where silt and clay laminae have been gently folded into an anticline. These features may in fact be syndepositional features, that is, affected by the current that deposited them, rather than

post-depositional features. Others may be the result of differential loading and would therefore be classified as post-depositional deformation structures.

4.3 The Sunwapta Lake Cores: Description and Analysis

4.3.1 General

On the basis of their known location within the lake, and the predominant sedimentary structures visible in each core, the seven cores can be divided into one intermediate, three south basin and three north basin cores (Fig. 6). The south basin cores are:

1. Core 2, 86cm long, collected near Pan B,
2. Core 3, about 68cm long, taken south and slightly east of Core 2, and
3. Core 4, the most easterly core of the three, collected southeast of Core 3. A portion of the tip of Core 4 has broken off and the overall length remaining is approximately 86cm.

The north basin cores are:

1. Core 1, 65cm long, collected south of, and between Pans 2 and 2A,
2. Core 6, about 94cm long, taken in the centre of the north basin, west of Pans 2 and 2A, and
3. Core 7, about 60cm long, collected in the northeast section of the north basin, opposite the Mt. Athabasca stream delta.

Core 5, the west channel core, occupies an intermediate

position, in terms of sedimentary structures, between the north and south basin cores. Core 5 was collected in the north basin, north of the west channel.

4.3.2 The South Basin Cores

The most distinctive feature of Core 2 (Fig. 27A) is the horizontal lamination present throughout the core. Very faint, fine-grained sets of laminae alternate with sets of silt and fine-to-coarse sand laminae, forming what appear to be larger sedimentation units. However, these units are not clearly defined, nor are they divided into distinct fine-grained and coarse-grained beds; rather, the sedimentation units are the result of gradual variations in number, thickness, grain-size and distinctiveness of laminae. The units range rather widely in thickness, so it is unlikely they represent the regular seasonal changes in sediment input and accumulation that distinquish varves. On a general basis, the units vary from 10 - 20cm in thickness. The top 2cm of the core consist of a structureless fine sand bed overlying very thin, disturbed laminae folded into an anticline. The subjacent 2.5cm consists of alternating silt and sand laminae. Fifteen centimetres from the top of the core, silt and fine-to-coarse sand form very distinct lamination; several coarse laminae are 2 - 3mm thick. An unusual bed of thick (2 - 3mm) alternating laminae of fine sand and coarse silt with quartz grains appears between 22 and 24cm from the sediment surface. Predominantly sand

FIGURE 27 A.	CORE 2:	SOUTH BASIN
B.	CORE 3:	SOUTH BASIN
C.	CORE 4:	SOUTH BASIN
D.	CORE 1:	NORTH BASIN
E.	CORE 6:	NORTH BASIN
F.	CORE 7:	NORTH BASIN
G.	CORE 5:	WEST CHANNEL

LEGEND

HORIZONTAL LAMINATION:

SAND

SAND AND SILT

SILT AND CLAY

STRUCTURELESS AND POORLY LAMINATED BEDDING:

SAND

SAND AND SILT

SILT AND CLAY

CURRENT RIPPLE CROSS - LAMINATION

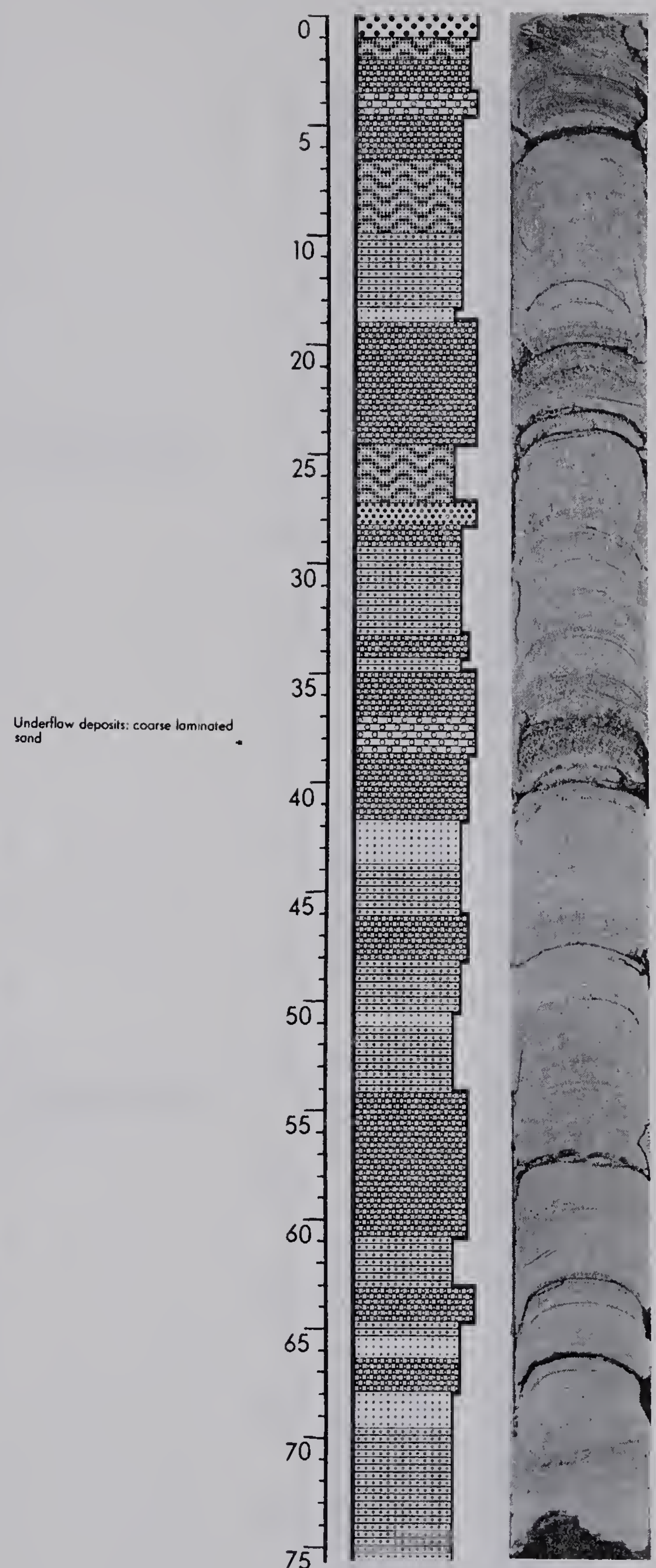
DISTORTED AND CONVOLUTE LAMINATION AND INTERLAMINATION

SLUMP STRUCTURES

FLAME STRUCTURES

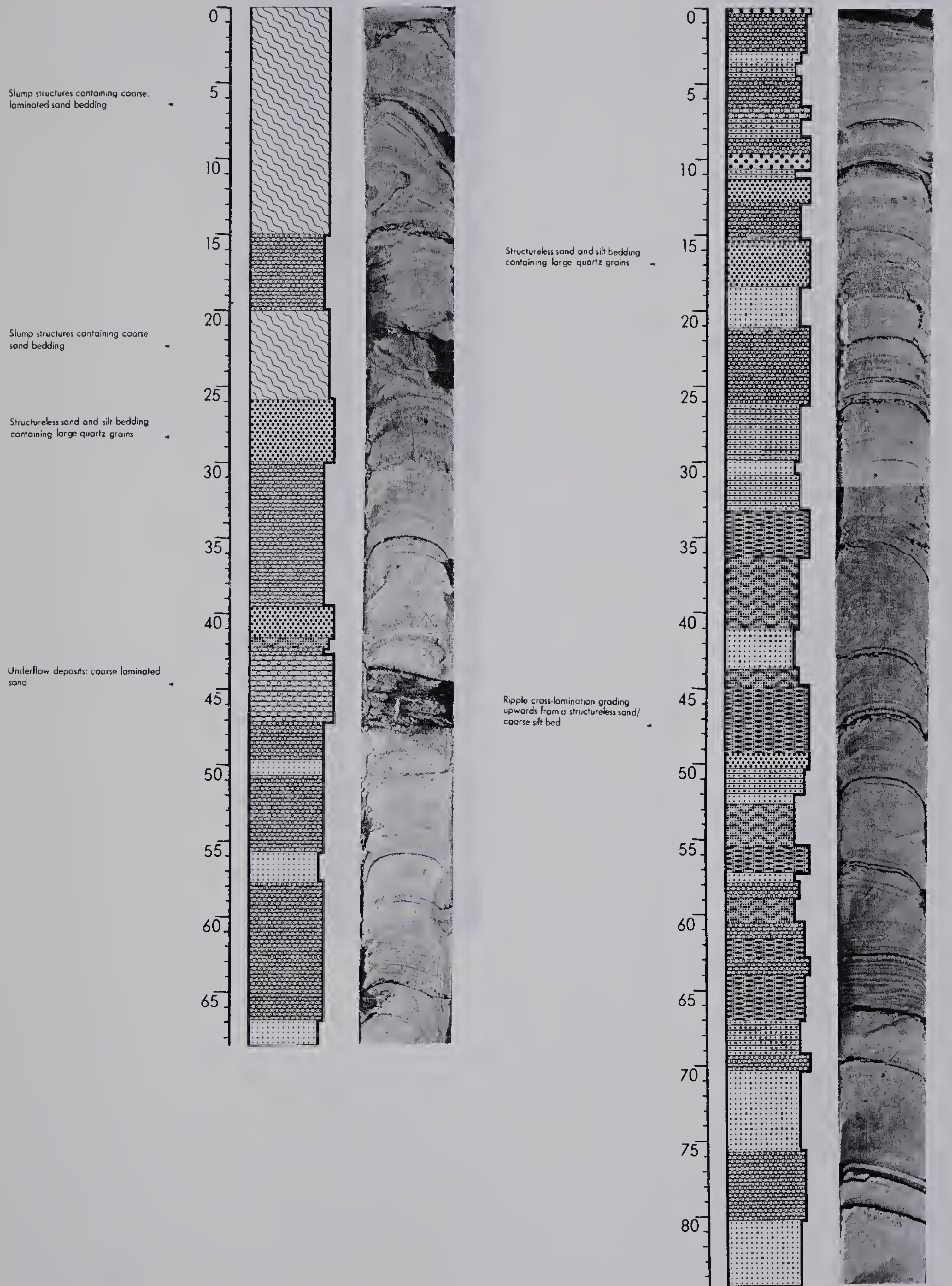
DROPSTONE

vertical scale in cm



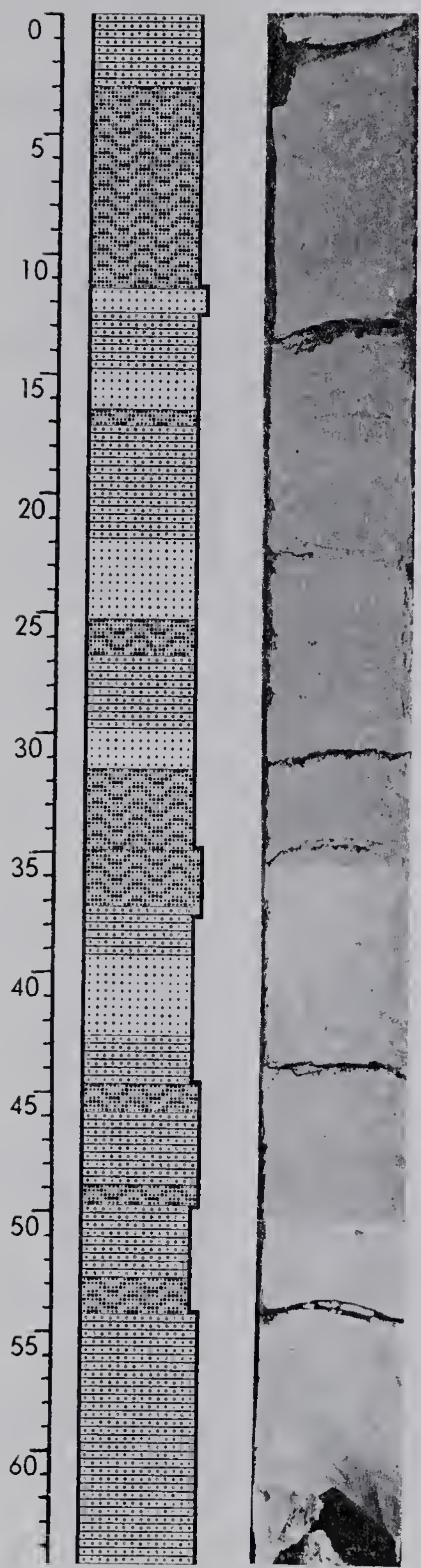
A

Some discrepancies are apparent between core diagrams and core photographs because a number of structures shown in the diagrams were visible when the cores were still damp, but are not visible in the photographs; this is due to photographic reproduction and the fact that the photographs were taken when the cores were somewhat drier.


Slump structures containing coarse, laminated sand bedding
Slump structures containing coarse sand bedding
Structureless sand and silt bedding containing large quartz grains
Underflow deposits: coarse laminated sand
Structureless sand and silt bedding containing large quartz grains
Ripple cross-lamination grading upwards from a structureless sand/coarse silt bed

B

C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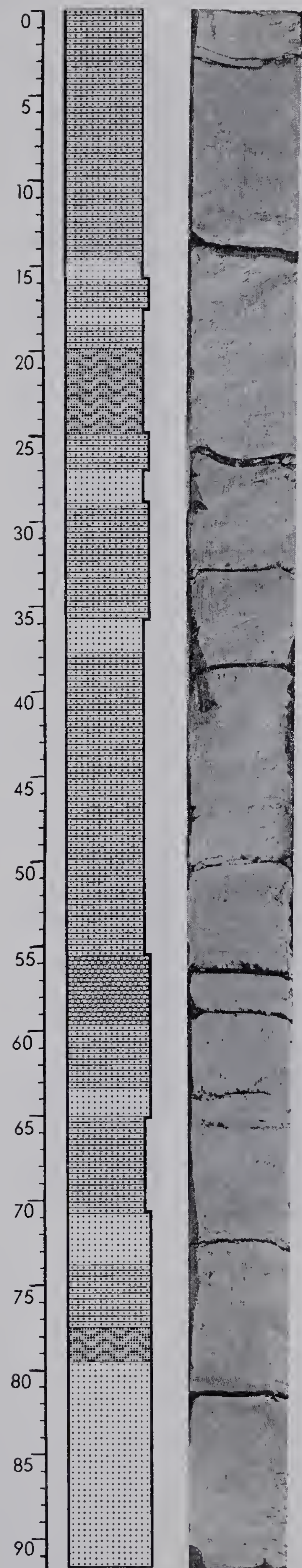
D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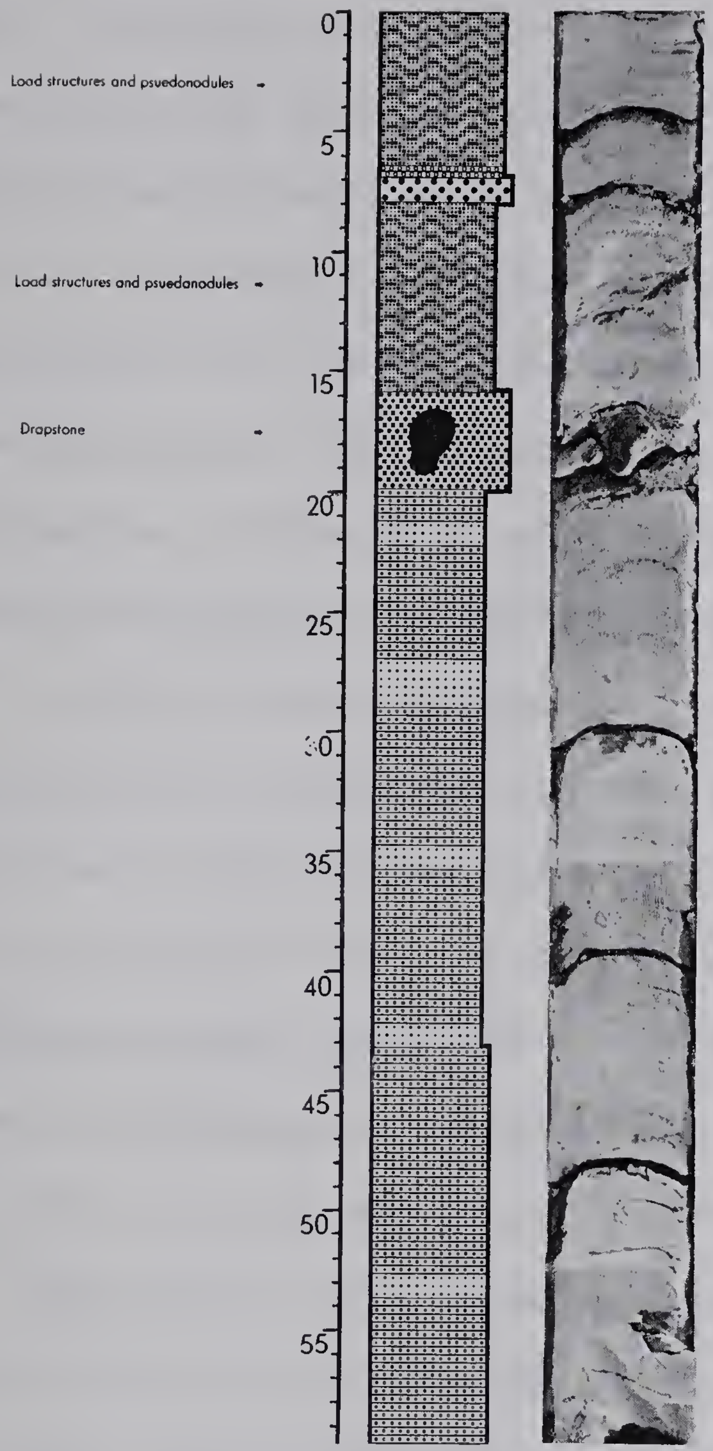
E


Load structures and psuedonodules
Load structures and psuedonodules
Dropstone
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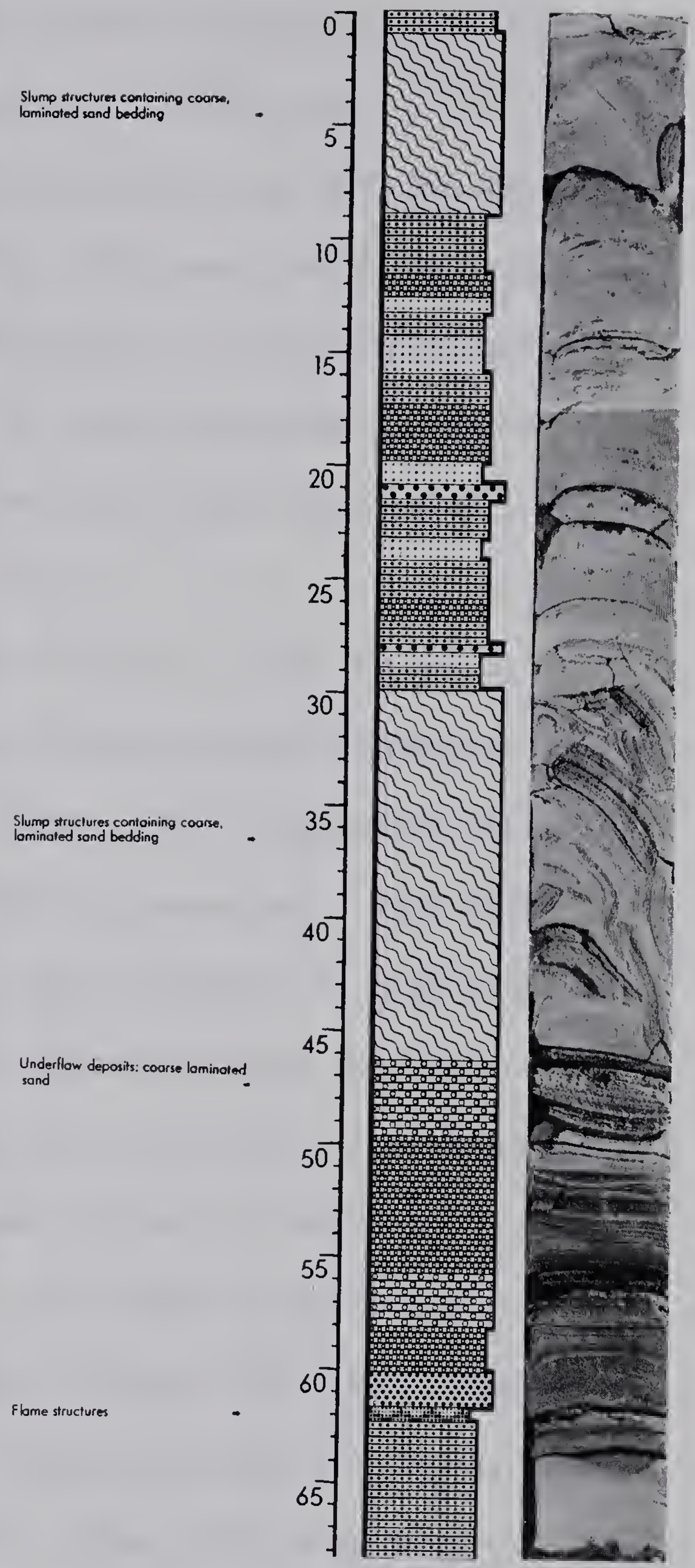
F


Slump structures containing coarse, laminated sand bedding
Slump structures containing coarse, laminated sand bedding
Underflow deposits: coarse laminated sand
Flame structures
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G

laminae lie between 28 - 29cm, 30 - 32cm, 49 - 55.5cm and 57.5 - 58.5cm from the top of the core. A sedimentation unit consisting of several beds of structureless and poorly-laminated coarse sand lies between 32 and 34.5cm. The unit is inversely graded, with the coarsest sand bed (about 1cm thick) at the top. Several examples of interlamination are present in the beds or sets of fine-grained laminae. Lamination at the base of the core has been disturbed, most likely during the coring operation.

Most of the top 26cm of Core 3 (Fig. 27B) have been disturbed by slumping. Coarse and fine-grained laminae and beds have been folded into anticlines and recumbent folds. It is possible that two slumps are represented, and the slightly folded parallel laminations between 15 and 20cm mark an interval of undisturbed sedimentation. The slump material is predominantly fine-grained but several laminae, 5 - 10mm thick, of medium sand are present. Two thick (1.5 - 2cm) strata of structureless silt and fine sand with numerous quartz grains are visible between 26 and 30cm, separated and bounded by beds of fine-grained laminae. This resembles the coarse silt bed 22 - 24cm from the top of Core 2. From 43 - 47.5cm from the sediment surface of Core 3, a bedding sequence of poorly laminated and structureless coarse sand forms a distinctive unit. The remainder of the core, from 47.5 - 69cm, consists of well-developed sets of silt and sand laminae, each lamina about 1mm thick, alternating with faintly laminated or structureless beds;

these units resemble the apparently rhythmic sedimentation units found in Core 2. As in Core 2, the units range in thickness from 10 - 20cm.

A small portion of the top of Core 4 has been lost. The first 2cm consist of several thick laminae of fine sand, and thinner laminae composed of sand, silt and clay (Fig. 27C). Core 4 lacks the very coarse sand units found in Cores 2 and 3. However, Core 4 contains several beds of current ripple cross-lamination. The better-developed examples lie between 44.5 - 50cm and between 61 - 67cm from the top of the core. The former grades upward from a bed of poorly laminated sand to current ripple cross-lamination to 'wavy' silt laminae. The latter follows a similar sequence, except that it lacks the subjacent structureless sand bed, and the ripples are composed of thicker laminae. Poorly developed ripple cross-lamination (perhaps viewed normally or tangentially to current flow) lies between 33.5 and 42.5cm. Unlike Cores 2 and 3, in which the laminae are largely horizontal and undisturbed, Core 4 contains numerous instances of disturbed fine-grained laminae. Lamination is wavy, folded into anticlines, or interlaminated. The top half of Core 4 contains more poorly laminated or structureless beds of silt and fine sand, than do either Core 2 or Core 3. Eight centimetres from the top of the core lies a 2.5cm thick bed of horizontally laminated sand and silt. Below this is a centimetre-thick stratum of sand. The bed has been disturbed by coring and drying, but appears to be poorly laminated. A

bed of coarse silt/sand/large quartz grains, 3.5cm thick and about 16.5cm from the top, resembles a bed present in both Core 2 (22 - 24cm from the top) and Core 3 (26 - 30cm from the top). The bottom half of Core 4 is apparently divided into sedimentation units similar to those in Cores 2 and 3.

4.3.3 The North Basin Cores

Core 1 (Fig. 27D) is composed solely of fine-grained material - silt and clay. When damp, the core sections composed predominantly of clay appear as dark laminae or apparently structureless beds of varying thicknesses. Similarly, sections composed predominantly of silt appear as light-coloured laminae or apparently structureless beds of varying thicknesses. No definite annual or other rhythmic sedimentation pattern is clearly visible in the core. However, sets of well-developed silt and silt/clay laminae are present at intervals throughout the core. The better-developed laminae lie between 9 - 11cm, 20 - 22cm, 28 - 30cm, and 46 - 52cm from the sediment surface. These laminations are generally adjacent to poorly defined laminae or thick (about 0.5cm) alternating laminae of silt and silt/clay. Also appearing at intervals throughout the core are relatively thick (several centimetres), apparently structureless or poorly-laminated, predominantly clay beds. The best examples occur between 15 - 16.5cm, 22 - 25.5cm, 30 - 31.5cm, and 39.5 - 43cm. Several of these beds show possible grading or inverse grading; others grade abruptly

from, or into, silt beds. The sets of laminae and the poorly structured or structureless beds may form larger sedimentation units averaging 6 - 9cm in thickness. However, there are no definite boundaries separating one unit from another. Also visible in Core 1 are several instances of distorted fine-grained lamination. Wavy and 'pinched out' laminae occur between 3 - 4cm, 16.5 - 17cm, 25.5 - 27cm, 31.5 - 33cm, 45 - 46cm, and 49 - 50cm. Between 35 and 37cm from the top of the core, fine-grained laminae have been folded into an anticline. Between 52 and 54cm, sections of the overlying clay sediment bed disrupt the underlying, faint silt laminations.

With the exception of some fine sand laminae between 56 and 60cm, Core 6 (Fig. 27E) consists of silt and clay, with horizontal lamination the dominant primary sedimentary structure throughout the core. Several beds, 2 - 3cm thick, appear structureless, but may actually contain laminations or grading not visible to the eye. As in Core 1, the more distinct sets of laminae appear at intervals, ranging from 6 - 10cm, from the sediment surface to the base of the core. Some disturbance of the horizontal lamination occurs between 20 and 25cm and again between 78 and 80cm from the top of the core.

Like the other north basin cores, Core 7 (Fig. 27F) consists largely of horizontally laminated silt and clay. The more distinct laminae occur between 34 and 36cm and between 44 and 46cm from the sediment surface. Two

features stand out in Core 7:

1. The large dropstone, about 16.5cm from the top of the core, and
2. The post-depositional deformation structures in the upper 10cm of the core.

The top of Core 7 is unusual in that it contains coarser sediment than is found anywhere else in the three deep north basin cores. Several thick (about 0.5cm) laminae of sand and coarse or fine silt contrast with distinct silt and clay lamination. Deformation of the horizontal laminations appears to be the result of differential loading of the coarser material on the mud laminae. This has created load casts and pseudonodules. The intervening sections of undisturbed horizontal lamination suggest that the deformation was not due to slumping. About 16.5cm from the top of Core 7, a large pebble with an apparent long axis 2.5cm in length, appears as a dropstone in the soft bottom sediments. Three centimetres' thickness of underlying sediment was disturbed. The pebble may have been thrown, but the distance from shore makes this unlikely. It is probable that the pebble was ice-rafted.

4.3.4 The Intermediate Core

Core 5 (Fig. 27G) combines features similar to those in Cores 2, 3 and 4, with features visible in Cores 1, 6 and 7. The top 31cm of the core consists of fine-grained horizontal laminations, with one exception; slump structures are

visible between 2 and 10cm from the sediment surface. Fine-grained and fine sand laminae have been folded into anticlines and recumbent folds. A fragment of a poorly laminated sand bed at least 1cm thick has been included in the slump material. Distinct horizontal lamination is visible between 12 and 13cm, 17 and 19cm, and between 25 and 27cm. Two fine sand laminae, each about 2mm thick, are present, one at 21.5cm and the other at 28.5cm.

Sedimentary structures and predominant grain-size change abruptly below 31cm. From 31 - 64cm below the sediment surface, over 50 percent of the sediment is of sand size. The sand is present either as structureless or poorly laminated beds 2 - 4cm thick, or as laminae 0.5 - 2mm thick, alternating with silt laminae. From 31 - 46.5cm, both coarse-grained and fine-grained bedding and laminations have been folded and fragmented by slump activity. From 46.5 - 64cm, the horizontal beds and laminations are undisturbed. A sedimentation unit of poorly laminated coarse sand lies between 46.5 - 50cm; the unit appears to grade upward from very coarse to coarse sand and then inversely upward from coarse to very coarse sand. A unit of laminated sand (with some silt laminae) between 51 and 55cm resembles the fragments of laminated sand bedding present in the slump material described above. A second laminated sand bed containing some silt laminae lies between 56 and 58.5cm.

Several examples of disturbed laminae are present. A narrow bed of what may be ripple cross-lamination is visible

between 52 and 53cm. At the base of a fine sand bed, 2cm thick, fragments of the underlying, apparently structureless silt bed have been incorporated into the sand as fragments and wisps or 'flame structures'.

4.3.5 Analysis and Discussion

With several exceptions, most notably the coarse structureless and poorly laminated sand units, the sedimentary structures visible in the seven cores are not distinctive, isolated features. Ripple cross-lamination grades upward into wavy and horizontal lamination. Faint laminae appear in the midst of thin structureless bedding. Fine-grained lamination grades inversely upward into coarse-grained lamination which in turn, grades into fine-grained laminae or structureless beds. Therefore, while rhythmic sedimentation units are visible to some extent in all seven cores, there are no abrupt distinct boundaries within, and between, units. Clear-cut annual deposits (varves), often described in studies of glacial lake sediments, are not visible in either the south basin or the north basin and intermediate cores. This may be the result of several factors:

1. The relatively small area of the two basins,
2. The location of the basins with respect to the sediment source,
3. Lake currents of high velocity associated with high discharge,

4. Katabatic winds associated with high temperatures,
5. The shallow depth of both basins, and
6. Underflow and slump activity.

The first four factors combine to hasten the movement of suspended sediment out the lake. The last two factors promote rapid settling and deposition of both coarse and fine material. Sunwapta Lake has been shown to be an effective sediment trap (Mathews, 1964b; Gilbert, 1975a), but almost all sedimentation occurs before winter. By the end of the melt season, little sediment is left in suspension to settle out and form the structureless or graded clay 'winter' varve beds. In addition, underflow and slump activity may introduce new material in winter, or remove in spring whatever fine-grained material has settled out between freeze-up and break-up. Therefore, the simple and complex varves described by Antevs (1931 and 1951) and others are not present in the Sunwapta Lake cores. Nevertheless, rhythmic, apparently cyclical sedimentation units defined by variations in number, thickness and grain-size of lamination, are visible in all seven cores. It seems likely, as discussed below, that the small-scale rhythmic deposits (measured in millimetres) represent daily (or slightly longer period) fluctuations in sediment input; the large-scale rhythmic units (measured in centimetres) represent annual melt season deposition. The latter includes coarse-grained laminae, distorted and contorted laminae, and such turbidity underflow features as coarse structureless

beds and ripple cross-lamination.

The lack of well-defined annual deposits (varves) makes it difficult to distinguish the sediment and structures of one year from those of another year. Correlation between cores is hindered by the scarcity of marker beds; very similar beds or bedding sequences, such as graded underflow deposits or sets of silt and sand laminae, may in fact have been produced by two or more events, either simultaneously or with a time difference ranging from several seconds to several years. Without observing or recording the underwater progress of a turbidity underflow or slump, there is no way of knowing whether an event affected one or more core sites. It is not unlikely that an underflow travelled over one site and bypassed another. The next underflow may have reversed the situation. Furthermore, underflows can travel in 'pulses' and, unless they are checked abruptly, gradually dissipate with the overall velocity decaying through the flow regimes. The massive, graded or poorly laminated sand deposits of one core could be related to ripple cross-lamination or deposits from suspension - fine-grained tail sediment - in another core site. Erosion of material by high-velocity currents can create discrepancies between two cores. Slumping can distort deposits and structures such as horizontal or cross-lamination; at the same time, material not deposited in a core area may be included in the slump material and transported to the core site. The distance between two cores and their respective locations within the

lake influence the process or processes of deposition and the relative effects of an underwater event on the core areas. The size and shape of the lake basin affects the results of a subaqueous current or slump. Without continual monitoring of discharge and sediment input from year to year, it is difficult (and perhaps misleading) to relate the data concerning sedimentation collected in one year to the events of previous years.

However, several important factors relating to sedimentation in Sunwapta Lake are known or inferred, and these factors greatly influence the analysis of the seven cores. Sunwapta Lake is divided into two basins by an intervening bedrock ridge; this has affected sediment distribution and deposition in the lake to a greater or lesser extent, depending on the location of the major sediment source. At some time between 1950 and 1956, the Athabasca Glacier retreated to a line south of the ridge (Fig. 2). The two basins, the north basin and the smaller south basin, have been in existence at least since the time of Mathews' sediment transport study in 1957 (Mathews, 1964b). A second major factor affecting sedimentation in Sunwapta Lake has been the changes in location of the major sediment source or sources. Not only have the three main streams migrated over their respective deltas, but the relative importance of the southeast and southwest streams has changed over the years (Mathews, 1964b; Gilbert, 1975a). These two factors, the intervening ridge and the changing

sediment source, should be evident in core samples taken in Sunwapta Lake.

The south basin is the proximal zone. Since at least 1957 (Mathews, 1964b), the south basin has constituted, or been included in, the zone of rapid sedimentation. In 1957, the sedimentation rate was estimated at 0.5 gm/cm²/day. It was suggested that the top 10 - 20cm of sediment cores taken from the deeper section of the lake, in the zone of rapid sedimentation, represented one year's deposits.

In 1975, discharge recorded in the Sunwapta River (and, from July 2 to August 21, in the southeast stream, see Fig. 17 and 18) followed the general pattern shown by the mean of mean daily flow in the river for the years 1948 - 1972 (Gilbert, 1975a). Flow began in mid-May, reached its maximum peak in early July, peaked again at the end of July/beginning of August, and tapered off, erratically, to freeze-up in mid-to-late October. Sediment input for the 1975 melt season, based on suspended sediment concentration and sediment pan data, show a general correlation with discharge (Fig. 19B); that is, the highest sedimentation rates and heaviest concentrations of suspended sediment occurred at the beginning and end of July (approximately July 5 - 15 and July 25 - 31). (As discussed in Chapter 3, the correlation frequently breaks down when examined for particular instances.) The south basin cores were collected on July 31, at the end of the most active period of the melt season. Estimated and measured sedimentation rates for zone

A (the zone of rapid sedimentation, see Fig. 26) suggest a thickness of 9 - 10cm of sediment deposited between May 15 and July 31. This would include material deposited by turbidity underflows and material settling out from suspension.

That turbidity underflows occurred in the south basin seems reasonably certain. An underflow was monitored by velocity meters on August 17/18, 1974 (Gilbert, 1975a), and conditions conducive to underflow activity were noted at the beginning and end of July, 1975. Furthermore, certain features visible in the cores, (coarse structureless and poorly laminated sand units, ripple cross-lamination, laminated silt and coarse sand), at present, can only be attributed to turbidity underflows as described by Kuenen (1951), Bouma (1962), Sanders (1965), Walker (1967) and others. It is possible that the coarse sand deposits about 33cm and 43cm from the top of Cores 2 and 3 respectively and the current ripple cross-lamination beginning at 45cm from the top of Core 4 represent the same underflow event. This idea is reinforced by the fact that underlying sequences of structureless and poorly laminated beds alternating with sets of well-developed laminae show a rough correspondance between cores. This is shown, for example, by the lamination 56 - 57cm from the top of Core 2 and the lamination 60 - 61cm from the top of Core 3. If the slump material comprising the first 10 - 15cm of Core 3 is considered to be sediment redeposited by slumping from outside the core area,

then the coarse sand unit actually lies about 28 - 30cm from the sediment surface. Another underflow, or a grain-flow, may be represented by the coarse silt/fine sand beds with large quartz grains found in Core 4, 16 - 20cm from the top, in Core 2, 22 - 24cm from the top, and in Core 3, 26 - 30.5cm from the top (or about 16cm below the base of the slump material). These underflow deposits, with the exception of the ripple cross-lamination, do not reflect velocity decay, but lie uncomformably below fine-grained sediment. Sanders (1965) has suggested that a coarse-grained bed overlain abruptly by a fine-grained bed represents deposition of the traction load of a underflow followed by deposition of material from turbulent suspension.

The sand beds, the current ripple cross-lamination visible in Core 4, and the slump material at the top of Core 3 probably represent single, isolated, relatively large-scale events. The remainder of the core sediments consist largely of material accumulated gradually over varying periods of time. In 1975, it was estimated that a layer of sediment averaging 14 - 15cm in thickness was added to the bed of the south basin during the melt season. If, as discharge records seem to indicate, the mean daily discharge of the source stream (and therefore, to a large extent, the sediment input) in 1975 is fairly representative of melt season mean daily discharge, then an average thickness of 14 - 15cm of sediment has been added to the south basin each year in recent years. The apparently rhythmic sedimentation

units in all three cores range in thickness from 10 - 20cm. It is probable that these units represent annual melt season deposition. Because there are no distinct boundaries, the deposits of one year merge imperceptibly with the deposits of the previous and succeeding years. However, the distinct sand/silt laminations present at relatively regular intervals along the length of each core probably indicate periods of maximum discharge and sediment input for each year. July and early August, on the average, is the time of maximum sustained flow (Gilbert,1975a). Mathews (1964b) and Gilbert (1975a) suggested that the distinct lamination, in the order of 0.5 - 5.0mm thick, present in cores collected in 1957 and 1974 respectively, recorded diurnal fluctuations in sediment input. In 1975, from July 4 - 31, when the cores were taken from the south basin, an average daily thickness of sediment in the order of 1.5 - 3.5mm was added to the lake bed south of the island. Total accumulated thickness for this period was approximately 6.25cm. The top 5cm of Core 2 forms a unit consisting of well-defined sand and silt laminations overlying poorly laminated silt, and underlying a structureless coarse sand bed about 1cm thick. From discharge records and estimated sedimentation rates (Fig. 18, Table 4A and 4B), it appears likely that the laminations represent the daily input of sediment from July 3 to July 31. If the coarse-grained lamination at the base of the unit is considered to represent the July 3 influx of sediment, approximately 25 - 30 laminae can be counted

between the base and the coarse structureless bed at the surface. (Individual laminae are not always distinctive.) Maximum daily sediment input was recorded between July 3 and July 7. The base of the unit consists of a centimetre of poorly laminated sand with little silt; this may be the deposits of the period of high discharge, highest sediment input, and high-velocity lake currents which transported a large proportion of silt and clay rapidly into the north basin. From about July 7 - July 15, both sediment input and discharge remained high; this period is recorded by approximately 10 well-defined sand and silt couplets. Between July 15 and July 24, discharge dropped, and sediment input, in contrast with previous periods, was low and stable. Average daily sediment accumulation was the lowest of any time interval between July 3 - 31. On July 24, discharge and sediment input rose and remained high until early August. The quieter interval of mid-July may be represented by the faint silt lamination and occasional fine sand lamina between 1.5 and 3.25cm from the sediment surface. The range between day and night temperatures was reduced, the lake was relatively calm, lake level was comparatively low, and sediment input probably did not vary greatly over diurnal periods. Conditions on July 24 were conducive to underflow activity, but whether the sand bed at the top of Core 2 was deposited on July 24 or later cannot be determined definitely, as the subjacent material has been disturbed. The discrepancy between the thickness of

accumulated sediment estimated for July (between 6 and 7cm) and the actual thickness of sediment in Core 2, representing sedimentation in July, 1975, may be due to:

1. Erosion of previous deposits by turbidity underflow, or
2. The method by which sediment accumulation was calculated. The actual sedimentation rates measured for the three south basin sediment pans may have been affected by wash-out and entrainment of sediment already deposited in the pans, by slump-generated turbidity underflows redepositing material into the pans, or by spillage of soft bottom sediment over the pan sides. Furthermore, estimated sedimentation rates for the pans may reflect deposition from underflows that bypassed the Core 2 site.

Another unit consisting of coarse laminated sand and silt appears between 14 and 19.5cm from the top of Core 2. The pattern of mean daily discharge in the Sunwapta River for the 1974 melt season was somewhat different from that of 1975. Periods of high flow occurred approximately between June 17 - 28, between July 17 - August 7, and between August 17 (when an underflow was recorded in the south basin, see Gilbert, 1975a) and August 31. It may be that the coarse laminae present at 15.5cm and 16.5cm from the top of the core are underflow deposits associated with peak discharge on August 4 - 5 and August 16 - 18 repectively. The coarse-grained laminae record daily fluctuations; the finer-grained laminae reflect variations in sediment input

over a period of several days; that is, an interval of cool weather with little diurnal change in temperature, discharge, and sediment input.

The coarse sand and silt units appear to be concentrated in the upper half of the cores. It may be that the sediment in the lower part of the south basin cores corresponds to the coarse sediment and underflow structures in the lower part of Core 5, both reflecting a time in which the southwest stream, as the major sediment source, flowed directly into the north basin.

At least until 1957, much of the north basin was included in the zone of rapid sedimentation. Sedimentation rates ranged from 0.6g/cm²/day in the southeast corner of the basin to 0.001g/cm²/day at the distal end of the lake, and Mathews (1964b) suggested that a layer of sediment, 10 - 20cm thick, could accumulate in one year in the deeper sections. By 1974, and probably earlier, the south basin had become the proximal zone. Sedimentation rates calculated for the south basin in 1975 were often double those of the north basin. It was estimated that an average thickness of 6 - 7cm was added to the deep section of the north basin during the 1975 melt season; this was based on sedimentation rates ranging from 0.02 - 0.38g/cm²/day.

The cores collected in the north basin, with the exception of Core 5 (from the west channel), consist predominantly of fine-grained horizontal laminae. Well-developed, slightly coarser lamination appears at

irregular intervals, particularly in Cores 6 and 7. The remainder of the laminae are very faint and visible only when the core is damp. Several beds of silt or silt and clay appear structureless. The horizontal laminae are probably the result of fluctuations in sediment input during the melt season. However, the thickness of some of the laminae (up to and over 2mm) and the location of the north basin sites with respect to the ridge and the sediment source suggest that the laminae, in general, are not the result of diurnal variations in sediment input, but correspond to longer periods of stable weather conditions. Sets of coarse-grained laminae may record diurnal variations in sediment input during periods of warm weather and high discharge. From data collected in 1975, daily accumulation of sediment in the deep section of the north basin ranged in thickness from 0.05mm in the spring to 1.6 and 1.7mm at the beginning and end of July, respectively. In periods of warm weather, high-velocity currents entering the lake from the southeast stream, and to a lesser extent, from the southwest and Mt. Athabasca streams, transported somewhat coarser material by overflow, interflow and possibly underflow, out into the north basin. However, warm weather was accompanied by katabatic winds, waves, and lake currents which generated turbulence and, as in the south basin, retarded deposition of fine-grained sediment in suspension until calmer conditions prevailed.

The laminations make it difficult to distinquish one

annual or melt season deposit from another. Larger sedimentation units consisting of a set of well-defined lamination and a poorly-laminated or structureless bed (or bedding sequence) may each represent one melt season's deposits. On the other hand, several sets of distinct laminae may record several periods of high flow in one melt season. At 1975 sedimentation rates, deposits of about 13 - 14 years are represented in Core 6.

With the exception of the top of Core 7, Core 6 is the only north basin core containing sediment of sand size. The fine sand laminations in Core 6 may have resulted from a similar situation to that noted on the east delta in 1975, namely, the temporary flow of relatively high-velocity currents directly into the north basin. Alternatively, these laminae may have been produced when the southwest stream was the main source of sediment. The fact that Core 1 lacks well-defined lamination would suggest that the distinct laminae in Core 6 are related to flow from the southwest stream. Core 1 does contain minor features of disturbance: fine-grained rippled laminae, for example, between 26 - 27cm, 32 - 33cm, and 45 -46cm from the sediment surface; 'pinched out' or interlaminated sediment, for example, between 49 - 50cm; and laminae folded into anticlines, for example, between 35 - 38cm. These features probably resulted from the passage of currents. Anemometers and velocity meters in the south basin in 1974 related lake bottom currents to wind (Gilbert, 1975a). A similar situation may

exist in the north basin. Strong katabatic winds are associated with high air temperatures, which in turn, are associated with high discharge and large sediment input. The same environmental conditions that produced the clear-cut laminations in Core 6 (20 - 21cm, 32 - 36cm, and 56 - 60cm from the sediment surface) may have produced the disturbed laminae in Core 1 (16 - 17cm, 32 -33cm, and 53 - 55cm from the sediment surface). Alternatively, minor underflows originating in the southwest stream may have been responsible for the features of both cores. If minor turbidity underflows travelled as far as Core 6, depositing fine sand laminae in the area, the passage of dissipating currents may also have produced the fine-grained contorted laminae visible in Core 1. These latter features are on a very small scale, the thickest being less than 2cm. Since no sediment coarser than silt is present in Core 1, taken east of Core 6, a relationship between the sand and silt lamination and the disturbed laminae (which occur at approximately the same depth in each core) would suggest flow from west to east. This would be likely if the southwest stream were very active.

The coarser material, load structures and pseudonodules in the top 20cm of Core 7 may be associated with stream flow from the Mt. Athabasca delta. These are recent sediments. Core 7 was collected in the distal zone of the lake, with respect to the major sediment source. However, there were some high flow events in the Mt. Athabasca stream, for

example, in the early part of July, 1975, although this stream was relatively inactive through most of 1974 and 1975. These events may have generated density underflows which deposited the coarse sediment in the Core 7 area. Alternatively, or in addition, slumps on the Mt. Athabasca stream delta may have generated turbidity underflows affecting the Core 7 site. With the exception of the top 20cm of Core 7, there are no indications that the deep section of the north basin was the proximal zone at any time during the deposition of the cored sediments.

Unlike the other north basin cores, Core 5 does contain features which reflect a proximal location with respect to the sediment source. The very coarse sediment in the lower half of the core was probably deposited by turbidity underflows originating in the southwest stream. It is known that, in some years, the southwest stream was the major source of sediment. In 1974, main stream flow was directed east and southeast into the south basin. However, it is likely that at one time, main stream flow was directed northeast into the west channel, just as in 1957, main stream flow from the southeast delta was directly into the north basin. Furthermore, the southwest delta is susceptible to slumping, for the reasons outlined for the southeast delta (see Chapter 3). If the rate of sediment accumulation has remained relatively constant since the west channel became a zone of low to moderate sedimentation, then approximately 6 - 7cm thickness has been added each year for

the last 4 - 5 years. Well-defined lamination appears at intervals 5 - 7cm apart in the top 31cm of the core. This may reflect diurnal variations in sediment input during annual periods of maximum discharge. Slumping has introduced material into the core area. The coarse laminated sand units included in the slump material 31 - 47cm from the top of the core resemble a sand unit visible between 51 and 55cm. The relatively high proportion of fine-grained material in the slump section suggests that the slump occurred some time after the laminated sand bed was deposited. Some of the silt and clay may be the fine-grained tail deposits which, having settled out from suspension after the coarser material was deposited, increased the pore water pressure and initiated the slump. Similarly, the coarse material present in the slump section 1.5 - 10cm from the core top may be material redeposited from outside the core area. This coarse sediment would, therefore, have little to do with sedimentation processes active at the core site at the time of the slump; in fact, the sand deposits could be several years old.

Sunwapta Lake is a small lake, only 0.8km in length. It is very likely that, without the intervening ridge, turbidity underflows could travel across the lake to the distal zone. Prior to the glacier's retreat south of the island and the establishment of the south basin as the main recipient of sediment, density underflows probably affected the north basin. As discussed in Chapter 3, the ridge has restricted underflow, and to a lesser extent, interflow,

activity to the south basin. This is evident in the lack of structures in the north basin cores associated with underflow activity. With few exceptions, the core deposits suggest relatively stable conditions of sedimentation in the deep section of the north basin, at least in recent years.

Sunwapta Lake has been shown to be an effective sediment trap (Mathews, 1964b). Echo soundings in the lake in 1973 and 1974 (Gilbert, 1975a) showed two reflecting horizons. The upper horizon was thought to be the surface of the lake bed sediments; the lower horizon, the surface of the non-lacustrine deposits. Measured thickness of lacustrine sediment ranged from less than 2m along the shoreline to over 9m in the deep sections of the north and south basins. There is too much sediment in the deep sections to be accounted for by the measured sedimentation rates of 1957 and 1975. Several factors may explain this discrepancy:

1. The retreat of the glacier caused changes in the location of the proximal, intermediate and distal zones. As late as 1957, estimated sedimentation rates in part of the north basin were almost twice as high as those calculated for 1975.
2. The Mt. Athabasca stream at one time may have contributed much more sediment than at present.
3. Melting and calving of the ice front when it formed the southern boundary of the lake probably deposited large quantities of sediment directly into the lake.

4. Slumping redeposited material from the steep slopes of the deltas and ridge into the deep sections of both basins.

It is significant that the northern part of the lake, presently the distal zone, has relatively gentle slopes and is furthest from all sediment sources. A thickness of only 2 - 4m of sediment was indicated by echo soundings in the north section of the north basin, although this is the oldest part of the lake.

5. Summary and Conclusions

A proglacial lake is formed when meltwater is ponded between the glacier margin and a barrier such as a bedrock ridge or moraine. Because of its proximity to a glacier, a proglacial lake is often characterized by a large and variable input of suspended sediment corresponding to seasonal and longer- (over a period of years) and shorter- (hourly or daily) term changes in glacier ablation (Østrem, 1969). It is this common characteristic that makes each proglacial lake unique and unpredictable. The factors affecting ice and snow melt and sediment supply, and therefore ultimately controlling proglacial lacustrine sedimentation, are many and varied. Some are of obvious importance: weather conditions, both long-term and short-term; the condition of the source glacier (retreating or advancing, cold-based or warm-based); the availability of eroded material; the discharge and variability in discharge of the influent stream(s); the size of the lake and the bathymetry of its bed; the location of the proximal, intermediate, and distal zones within the lake. Other factors may attain temporary importance: minor changes in the channel or channels of the source stream(s); jökulhlaups; additions of water and sediment from intermittent glacial and non-glacial streams; ice-rafting; conditions generating slumping; changes in groundwater flow. These and other variables control the delicate balance between sediment 'input' (supply) and 'output' (deposition

and outflow).

The study of an individual lake is, in itself, an academic excercise; conditions vary from lake to lake and within each lake through time and space. In a larger context, however, study of individual glacial and proglacial lakes is necessary for several reasons, including the need for comparison with laboratory experiments, and a search for common characteristics that will aid in the interpretation of present and past lacustrine processes of sediment distribution and deposition. The more controlled the laboratory environment, the less it resembles the natural environment. The constantly changing and interrelated variables that have produced the sedimentary structures now visible in cores and exposed sections cannot be reproduced in a laboratory. At the same time, direct observation of sedimentary processes in proglacial lakes is practically impossible. The relative importance of various factors can be more easily assessed under controlled laboratory conditions. Laboratory studies provide the clues as to what happens in a proglacial lake environment through time and space; field studies provide a measure of confirmation of laboratory findings.

Sunwapta Lake is a small, relatively shallow, proglacial lake adjacent to the Athabasca Glacier. From 1935, when the lake came into existence, until the early 1960's, when the ice margin no longer formed the southern boundary, the lake increased in area with the continued retreat of the glacier front. Since the mid-1950's, the lake

has occupied two basins, the original north basin and the smaller, more recent south basin. Growth of active deltas and the large input of sediment is gradually reducing the area and the depth of the lake; this is particularly true for the south basin which, since the late 1960's, has been the proximal zone. The lake is fed directly by meltwater streams, but the major source of water and sediment has changed several times since the lake's inception.

Cores collected from the lake bed clearly indicate variations, through time, in the location of the proximal and distal zones. Grain-size, sedimentary structures, and thickness of apparently annual deposits reflect the migration of the source stream and the division of the lake into two basins. Some of the changes known or thought to have occurred in the lake can be recognized in the cores.

Sediment pan data from 1957 (Mathews, 1964b) and 1975 show the effectiveness of Sunwapta Lake as a sediment trap; comparison of the 1957 data with that of 1975 shows the effectiveness of the bedrock ridge as a barrier to sediment distribution between the south and north basins. Total sediment accumulation in the lake from May 15 - October 15, 1975, was estimated at 14.5×10^3 - 16.2×10^3 metric tons. This compares with an estimated sediment input for the 1975 melt season of 19.7×10^3 - 21.0×10^3 metric tons and an output of 4,800 - 5,200 metric tons.

From statistical studies carried out on the Sunwapta River in 1959 and 1960 (Mathews, 1964a), Mathews concluded

that air temperature and percentage of sunshine had a much greater effect on run-off from the Athabasca Glacier than did precipitation or humidity. In 1975, meteorological data from the Jasper weather station were used to supplement general weather observations at Sunwapta Lake. In general, discharge in the southeast stream and the Sunwapta River varied with air temperature and amount of sunshine. A time lag of one to two days between changes in maximum daily temperature at Jasper and changes in mean daily discharge probably reflects the movement of weather patterns and the location of Athabasca Glacier with respect to Jasper. For the same reason, the relationship is poor at the beginning and end of the melt season.

A positive, but low correlation exists between discharge and suspended sediment concentration in the source streams of Sunwapta Lake. In general, concentration varies with discharge over the melt season, but the relationship breaks down when examined for shorter time periods. No hourly sampling of suspended sediment in the southeast stream was attempted in 1975, but a comparison of suspended sediment concentrations with mean two-hourly discharge readings shows very little correlation between discharge and concentration. The greatest visible point scatter on a graph occurs when afternoon discharge readings are compared with afternoon concentration measurements; many high discharge readings correspond with relatively low concentrations. In July and August, 1975, the highest concentrations recorded

occurred during periods of rising discharge. Concentrations generally fell while flow remained high. In many glacial meltwater streams, daily and seasonal peak concentrations of suspended sediment do not coincide with peak discharge measurements (Fahnestock, 1963; Østrem et al., 1967; Østrem, 1969 and 1975; Kennedy, 1975; Sugden and John, 1976). This has been attributed to rapid increases in discharge following periods of low flow causing erosion of unconsolidated streambed deposits (Kuenen, 1951; Kennedy, 1975) and/or accumulated material eroded by the glacier over the winter and not removed until spring melt (Sugden and John, 1976). Comparison of weather, discharge and concentration data for 1975 suggests that similar events occur in the southeast stream from Athabasca Glacier. Fluctuation in sediment supply is a major factor in proglacial lake sediment distribution. Differences in suspended sediment concentration create differences in density between stream water and lake water, and within the lake. Stratified flow results. In most proglacial lakes, including Sunwapta Lake, the large and variable sediment supply outweighs the effects of temperature differences or differences in dissolved sediment (see Kuenen, 1951). In 1974, a turbidity underflow was recorded in the south basin (Gilbert, 1975a). In 1975, an underflow was never actually recorded, but evidence suggests that all three types of density flow - overflow, interflow, and underflow - occurred in 1975, as well as in previous years. This evidence

includes:

1. Observation of sediment overflow 'plumes',
2. Observation of sediment plumes 'plunging' beneath lake water at the edge of shallow lake margins,
3. Observation and drogue movements showing variations in direction and velocity of lake currents,
4. Large fluctuations in sediment supply, both diurnally and over the melt season, calculated from discharge measurements and suspended sediment samples,
5. Variations in sediment concentration across the lake,
6. Variations in sediment concentration with depth within the lake, as shown by Van Dorn bottle samples,
7. Discrepancies between concentrations of suspended sediment in the stream and at the lake surface, suggested from suspended sediment samples,
8. Coarse-grained material in the centre of the south basin and the relative lack of coarse-grained material in the north basin, as shown by sediment pan samples,
9. The relative sedimentation rates between the south basin and the north basin, and within the north basin, as calculated from sediment pan samples,
10. The bathymetry of the lake bed, including steep delta foreset beds,
11. Variations in thickness of lake bed sediments indicated by surveys with a Raytheon high and low frequency sounder (Gilbert, 1975a), and
12. Sedimentary structures, grain-sizes, and thickness of

deposits present in cores collected in 1957, 1974, and 1975 (Mathews, 1964b; Gilbert, 1975a).

There has been some discussion as to whether turbidity underflows in proglacial lakes are more likely to occur in early spring, due to nival meltwater, or in summer, due to the high rate of glacier ablation (see, for example, Kuenen, 1951). Field studies at Sunwapta Lake during 1975 suggest that underflow activity is most likely to occur when a sudden rise in discharge follows a period of cool weather and low flow. This may happen at any time in the melt season, depending on weather conditions. Exceptionally high concentrations of suspended sediment in the southeast stream were recorded several times during July and August, 1975. These concentrations were generally associated with rising discharge, rather than with the highest discharge measurements; the latter were often associated with somewhat lower concentrations. That underflows are a relatively uncommon (as compared with overflows and interflows), but very important factor in sediment distribution in Sunwapta Lake is suggested by the cores, by the relative sedimentation rates, and by the proportion of coarse-grained material in the south and north basins.

The sedimentation intervals between replacement and recovery of each sediment pan in the south basin were generally too large to distinguish whether the high rates were due to one or more underflows, and when underflow activity occurred during an interval. However, the highest

sedimentation rates calculated for the south basin pans included periods of rapidly rising discharge. The highest sedimentation rate calculated for Pan B is for the period July 21 - 26. At this time, suspended sediment concentrations measured in the southeast stream were very low, with the exception of a sudden increase in concentration on the afternoon of July 24; this suggests that an underflow on July 24 supplied much of the sediment in Pan B, giving an average sedimentation rate of 0.630 $g/cm^2/day$ for that period. The second highest sedimentation rate of the field season for Pan C - 0.535 $g/cm^2/day$ - also occurred during the period July 21 - 26.

Study of underflow activity in Sunwapta Lake is complicated by the high probability of slumping. Slumping may have been responsible for some or most of the coarse material and the high sedimentation rates in the south basin. Conditions conducive to slumping, including rapid and heavy sediment deposition, fluctuating lake levels, and steep slopes (see Moore, 1961), were present in Sunwapta Lake during the summer of 1975. Deformation structures associated with slumps were found in both north basin and south basin cores.

Further study of the Sunwapta Lake cores may reveal statistical relationships between thickness of deposits, variations in grain-size, mean daily discharge or annual discharge (available from Water Survey of Canada), and weather information from the Jasper weather station or, for

some years, from the vicinity of the Columbia Icefield. The lake is small, with an easily identified major source of water and sediment. Annual discharge records are available for the Sunwapta River, from 1948 to the present. With the work already carried out in Sunwapta Lake and its source streams, Sunwapta Lake is considered to be an excellent site for continued study of lacustrine processes in proglacial lakes.

Studies carried out in Sunwapta Lake emphasize the highly complex nature of proglacial lacustrine sedimentation. Sediment distribution in Sunwapta Lake in 1975 was controlled by 1) fluctuations in sediment supply and 2) the bathymetry of the lake. The former determined the type of density flow - overflow, interflow or underflow - active in the lake at any particular time; the latter controlled the movements of the density flow in the lake. These two factors prevented a 'normal' proximal to distal association of grain-size, thickness of deposits and types of sedimentary structures. Without information on the bathymetry of the lake and the processes of sediment distribution, interpretation of Sunwapta Lake deposits would be extremely difficult.

Cross-valley ridges of till or bedrock are commonly associated with valley glaciation. If such a ridge existed in a lake where underflow activity was primarily responsible for sediment distribution, the resulting sedimentary deposits would show complex vertical and horizontal

variation. Firstly, deposition on the proximal side of the barrier would be intensified. This may lead to the erroneous interpretation of a higher rate of sediment input (and by inferrance, a higher rate of glacier melt). Secondly, confining an underflow to a small basin could preclude the formation of a 'Bouma-type' turbidite sequence. Whether or not underflow activity was continuous or 'catastrophic', the sudden checking of the current against the basin walls would be more likely to create the graded bedding of Kuenen and Migliorini's (1950) flume experiments than the coarse parallel laminations (or bedding) and cross-lamination (or cross-bedding) associated with gradual current velocity decay. This could create a false impression of the type of underflow that occurred in an ancient proglacial lake. For example, the underflow recorded by Gilbert (1975a) in August, 1974, appeared to be of a 'catastrophic' rather than a continuous nature; however, there was no indication of current velocity decay in the south basin cores, although coarse underflow deposits were present. If underflow in an ancient lake was related to variations in sediment supply (as appeared to be the case in Sunwapta Lake), then misinterpretation of turbidity underflow activity could lead to wrong conclusions concerning sediment input, stream discharge and glacial melt. Thirdly, deposits in the lee of the barrier would more closely ressemble deposits in a distal location. This was apparent in the Sunwapta Lake cores. Finally, the presence of a ridge could hinder the

formation of varves in the lee of the barrier. Since only overflow, and some interflow, material could be transported over the barrier, the sediment in the lee of the barrier would be relatively homogenous (silt and clay) and possibly more evenly distributed over the lake. In a small shallow lake (such as Sunwapta Lake) such material, if not carried out the lake, would rapidly settle out in calm conditions.

Varves were conspicuously absent in the Sunwapta Lake cores; thus, the yearly 'time-scale' often used in the study of ancient glaciolacustrine deposits was not applicable in this lake. Because sedimentation in proglacial lakes is seasonal rather than continuous, if any degree of uniformity of discharge existed from year to year, then some evidence of annual changes in sediment supply should be visible. The rhythmic sedimentation units present in the Sunwapta Lake cores appeared to correspond with measured sedimentation rates and recorded events in the lake. Therefore, these units were considered annual. However, field work indicated that short-term changes in weather (particularly temperature, as it affects glacial melting) during the melt season could be as important to sediment distribution as seasonal weather changes. The rhythmic units in the Sunwapta Lake cores are relatively regular in thickness. The thickness of individual units corresponds closely with annual sedimentation rates and, therefore, the units can be confidently identified as annual units. Regular thickness of rhythmic units in ancient deposits may also be used to

suggest an annual cycle. However, the degree of confidence will be much less in the absence of information on sedimentation rates. For instance, two or more major run-off events during a single melt season may lead to an overestimation of the number of years represented by a lacustrine sequence. The proximal deposits of a shallow lake lack the important 'winter clay' marker which is generally used in varve counting. The absence of a clear marker bed and the variability of sedimentary characteristics of lacustrine sediments of the Sunwapta Lake type make them unreliable in terms of estimating time.

If Sunwapta Lake is fairly representative, sedimentary processes and sedimentation in proglacial lakes are closely related to such 'external' factors as variations in sediment input, discharge, glacier melt, and weather conditions. With further study of proglacial lacustrine environments, it may be possible to measure and statistically analyse the relationship between these variables. Such measurements could then be used in the interpretation of ancient glaciolacustrine deposits and the environment in which they were formed.

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Appendix A

This appendix contains the sediment concentration data collected from Sunwapta Lake during the field season July 2 - August 21, 1975. The suspended and dissolved sediment concentration, in milligrams per litre, for the southeast stream, and at pan sites B, 1, 2, 3, and 4, and the outlet are shown in table A-1. The estimated sediment load, in metric tons per day, for the southeast stream is shown in table A-2.

Table A-1. Sediment concentrations in the south-east stream and in Sunwapta Lake.

Date	Suspended sediment (Cs) and dissolved sediment (Cd)															
	South-east stream			Sunwapta Lake												
				Pan B		Pan 1		Pan 2		Pan 3		Pan 5		Outlet		
	Time	Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Time
JUL 2	1200	347														
	1800	906														
	2000	1184		176.9		17.8		43.1		53.7						2000
JUL 3	1600	1468														
	2000	3156				48.4		90.0		107.8						2100
JUL 4	1200	1160				123.2		53.7		70.0						1200
	1700	1539														
	2000	1839		362.7		113.9		95.8		107.8						2000
JUL 5	1000	853				282.0		95.8		92.9						1000
	2000	2821				120.1		136.1		162.9						2000
JUL 6	1000	944				191.5		110.9		117.0						1000
	2000	1335				101.7		117.0		123.2		104.7				2100
JUL 7	1100	786														
	2000	869		296.0		264.1		117.0		142.6						2100
JUL 8	1000	444				78.4		84.1		84.1						1000
	1800	1670		368.4												1700
JUL 9	1000	714														
	1700	1374		300.8												1700
JUL 10	1000	506														
	1800	1227		255.4												1700
JUL 11	1000	452				206.6		159.4		139.3						0900
	1700	2567		325.6												1600
JUL 12	1000	783														
	1600	1850		385.6		184.2		162.9		184.2						1600
JUL 13	1000	415														
	2000	597														
JUL 14	0900	347														
	1900	995														
JUL 15	1000	285														
	1700	704														
JUL 16	1900	506		226.2		159.4		123.2		152.6				84.1		1000
JUL 17	1000	268				199.0										1200
														43.1		1600
	2000	569		273.0		159.5		136.1		117.0		95.8				2000
JUL 18	1000	431														
JUL 19	1000	401		156.0		98.7		95.8		101.7		110.9				1100
	2100	363						90.0								1600

Table A-1. Cont.

Date	Time	Cs	Cd	Pan B Cs	Pan B Cd	Pan 1 Cs	Pan 1 Cd	Pan 2 Cs	Pan 2 Cd	Pan 3 Cs	Pan 3 Cd	Pan 5 Cs	Pan 5 Cd	Outlet Cs	Outlet Cd	Time
JUL 20	1000	557														
	1900	463	24.0													
JUL 21	1000	425	36.4													
	1800	708	22.4	195.3	26.8	75.6	29.6	62.6	30.8	84.1	30.4			32.8	36.8	1900
JUL 22	1000	522	40.0			67.2		48.3	30.0	59.0	30.0	37.9	28.4			1000
	1900	682	22.8													
JUL 23	1000	341	34.0	139.3	27.6	48.3	24.0	59.0	27.6	59.0	28.0					1100
	1700	1037	18.0													
JUL 24	1000	815	33.6	199.0	28.0	87.0	27.6	17.8	28.0	87.0	24.8			48.3	34.8	1000
	1900	2358	27.6													
JUL 25	1000	1342	33.6													
	2000		37.8													
JUL 26	1000	827	22.0	238.5	25.6	180.5	24.8	149.3	26.0	156.0	26.0	139.3	26.0			1100
	1700		19.0	403.7	13.6	373.8	22.0	162.9	22.0	195.3	26.4	169.8	27.2	180.5	30.0	1800
JUL 27	1100	1390	22.0	169.8	25.6	180.5	24.0	156.0	24.0	149.3	25.6	162.9	24.0			1100
	1700	2253	19.6	264.1	22.4	149.3	25.6	123.2	26.0	136.1	25.6	156.0	25.2	156.0	27.6	1800
JUL 28	1100	801	21.6			184.2	22.8	162.9	24.0	184.2	23.6					1200
				300.8	24.0											
JUL 29	1000	690		176.9	30.0	92.9	25.2	92.9	26.4	117.0	26.4	90.0	26.4			1100
	1800	434	24.8													
JUL 30	1100	393	31.6	199.0	31.6	62.6	28.0	64.5	27.6	120.1	30.0	56.3	28.8			1200
	1800	502	31.2													
JUL 31	1000	217	42.8	120.1	35.6	43.1	28.0	53.7	30.0	32.8	31.6	53.7	32.0	53.7	38.0	1100
	1700	964	26.8													
AUG 1	1000	265	34.8													
AUG 2	1000	305	26.4													
	1900	282	32.8											72.8	40.8	1900
AUG 3	1000	144	39.2	92.9	31.6	110.9	30.0	75.6	30.8	59.0	32.4	53.7	31.6			1000
	1900	640	26.0	184.2	35.2	139.3	34.8	72.8	36.0	67.2	36.4	87.0	35.2	53.7	41.2	1900
AUG 4	1000	231	34.0	90.0	33.2	75.6	35.6	64.5	36.8	59.0	35.6	59.0	35.6			1100
	1700	753	21.2													
AUG 5	1000	973	31.6	169.8	30.8	159.4	26.0	90.0	34.8	95.8	36.4	87.0	36.8			1100
	1800	1935	24.4	206.6	24.4	123.2	25.2	126.4	25.6	129.6	26.8			84.1	40.8	1800
AUG 6	1000	824	38.8	48.3	34.8	53.7	31.2	32.8	36.0	43.1	34.0	27.7	32.8			1200
AUG 7	1000	169	42.0	92.9	36.8	64.5	36.8	37.9	34.4	27.7	34.8			25.2	38.8	1000
AUG 8	1100	87	40.8													
	1900	279	24.8	87.0	32.8	81.3	32.4	48.3	31.6	40.5	32.8			37.9	36.8	1900
AUG 9	0900	75	44.0	81.3	32.8	84.1	30.0	59.0	31.6	62.6	32.8					0900
	1800	855	23.6													

Table A-1. Cont.

Date	Time	Cs	Cd	Pan B		Pan 1		Pan 2		Pan 3		Pan 5		Outlet		
				Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Cs	Cd	Time
AUG 10	2000	507	24.0	101.7	34.0	72.8	36.4	64.5	38.0	84.1	36.8					1000
AUG 11	1900	548	32.8	120.1	27.6	64.5	30.0	70.0	32.8	98.7	31.2					1100
AUG 12	1000	127	44.4	95.8	32.0	78.4	32.8	53.7	32.8	59.0	34.0					1500
AUG 13	1000	120	42.8	101.7	30.0	70.0	31.6	64.5	32.8	48.3	34.4			37.9	40.8	1000
	1700	635	18.4	117.0	24.0	101.7	22.4	64.5	26.8	75.6	28.8			48.3	34.8	1700
AUG 16	1000	71	33.6	81.3	29.2	75.6	30.0	70.0	30.0	22.8	35.6					1000
AUG 17	1100	130	23.6													
	1900	130	28.0	81.3	27.2	78.4	28.0	48.3	30.0	32.8	31.2	95.8	30.4	43.1	32.8	1900
AUG 18	1000	86	34.0													
	1900	624	17.2											43.1	26.4	1900
AUG 19	1100	100	28.8	90.0	26.0	75.6	22.8	59.0	27.2	70.0	27.2	53.7	28.4			1100
AUG 20	1100	114	26.0	92.9	25.2	75.6	24.8	48.3	27.2	56.3	28.8					1100
	1900	692	22.0													
AUG 21	0900	120	22.4	87.0	26.0	75.6	26.0	67.2	28.4	59.0	30.0	64.5	28.8			1500

Table A-2. Sediment load in the southeast stream.

Date	Sediment Load Metric tons / day
JUL 2	153
JUL 3	786
JUL 4	584
JUL 5	892
JUL 6	654
JUL 7	454
JUL 8	554
JUL 9	503
JUL 10	453
JUL 11	891
JUL 12	886
JUL 13	306
JUL 14	412
JUL 15	289
JUL 16	215
JUL 17	161
JUL 18	156
JUL 19	118
JUL 20	145
JUL 21	157
JUL 22	168
JUL 23	181
JUL 24	623
JUL 25	649
JUL 26	420
JUL 27	1436
JUL 28	499
JUL 29	255
JUL 30	144
JUL 31	163
AUG 1	74
AUG 2	119
AUG 3	104
AUG 4	155
AUG 5	741
AUG 6	376
AUG 7	50
AUG 8	42
AUG 9	87
AUG 10	132
AUG 11	118
AUG 12	32
AUG 13	31
AUG 15	237
AUG 16	25
AUG 17	48
AUG 18	122
AUG 19	39
AUG 20	154
AUG 21	54

Appendix B

Statistical Methods used in the Text

1. Rating Curve for Stage versus Discharge

A non-linear relationship exists between stage (the height of the average water level above a datum point) and discharge (the volume of water passing through a given area in a given time interval - usually measured in cubic feet per second or in cubic metres per second). Using actual velocity and stage measurements, discharge was calcuted and plotted as points on a graph with stage, in centimetres, as the x-axis and discharge, in cubic metres per second, as the y-axis. Because the relationship is non-linear, the simple linear regression equation, $Y = A + BX$, does not apply. Instead, a log transformation is used. The equation for the regression curve can be expressed in the form:

$$Y = A \operatorname{Log}_{10}(X) + B \qquad \text{(B-1)}$$

The constants A and B were calculated using the Statistical Package for the Social Sciences (Nie et al., 1975).

Two regression curves were plotted for the southeast stream in the summer of 1975. The equation for July 2 - 5 is:

$$Q = 33.5 \operatorname{Log}_{10}(\text{Stage}) - 46.5 \qquad \text{(B-2)}$$

The equation for July 6 - August 21 is:

$$Q = 22.9 \, \mathrm{Log}_{10}(\mathrm{Stage}) - 31.5 \qquad \text{(B-3)}$$

in which Q is discharge measured in cubic metres per second, and Log_{10} (Stage) is the log of the actual height of water recorded in centimetres. The two regression curves are 'best-fit' lines. Standard error for equation B-2 is 0.252, and for equation B-3, 0.411.

Table B-1 shows discharge calculated from stage readings and fourteen velocity/area surveys. Table B-2 shows actual stage readings for two - hourly intervals, from July 2 - August 21, 1975. Table B-3 shows discharge for two - hourly intervals calculated from the stage versus discharge rating curves and measured stage readings.

2. Rating Curve for Suspended Sediment Concentration versus Transmissivity

A non-linear relationship was found to exist between the transmissivity and the suspended sediment concentration measured for lake water samples. The form of the equation is the same as the form of the equation form of the stage vs discharge rating curve. The actual equation of the rating curve is

$$C_s = 1641 \, \mathrm{Log}_{10}(T) - 834 \qquad \text{(B-4)}$$

in which C_s is suspended sediment concentration of the sample, and $\mathrm{Log}_{10}(T)$, the log of the transmissivity of the sample. The constants 1641 and -834 were calculated using the Statistical Package for the Social Sciences (Nie et al.,

Table B-1. Discharge and stage readings for the rating curves.

Rating curve	Discharge	stage
Jul 2 to Jul 5	2.77	29.6
	4.15	32.6
	5.35	34.4
	7.27	40.4
Jul 6 to Aug 22	6.13	43.8
	5.97	45.3
	6.03	42.6
	4.23	36.5
	3.95	35.3
	2.65	30.4
	2.63	30.7
	6.37	41.0
	3.10	33.7
	5.13	40.6

Table B-2. Stage readings (cm) for two-hourly intervals.

Date	Time											
	2400	0200	0400	0600	0800	1000	1200	1400	1600	1800	2000	2200
JUL 2							25.91	28.14	28.72	29.62	29.34	28.72
Jul 3	28.62	28.23	28.14	27.33	27.71	28.14	30.14	31.15	30.74	31.15	33.55	33.46
Jul 4	33.55	34.37	32.95	31.54	29.36	32.46	34.65	36.38	34.77	33.46	33.16	32.35
Jul 5	32.15	31.75	31.95	31.34	31.54	34.96	36.18	38.78	41.80	42.00	40.89	41.20
Jul 6	48.19	46.20	45.19	44.78	44.15	45.37	46.38	48.19	47.57	47.18	47.18	45.60
Jul 7	45.19	44.69	44.07	43.67	43.89	44.07	45.19	46.20	45.19	46.67	45.46	45.46
Jul 8	43.67	42.84	41.36	40.17	40.17	41.24	44.15	46.57	50.52	47.71	45.37	41.65
Jul 9	40.95	39.45	38.55	37.33	37.25	38.43	41.15	43.19	46.20	49.17	46.20	43.19
Jul 10	41.15	39.65	39.14	40.17	41.15	42.16	44.29	46.67	48.19	48.68	47.37	46.38
Jul 11	45.69	44.69	44.07	43.19	42.67	43.98	46.20	48.00	50.22	52.23	53.24	54.21
Jul 12	54.21	52.02	50.52	49.47	49.17	50.22	53.02	52.23	52.23	53.99	53.50	53.24
Jul 13	50.68	48.87	47.18	46.20	45.37	45.69	46.20	47.00	48.00	50.22	51.39	50.22
Jul 14	49.17	47.00	45.97	45.19	44.69	44.15	47.37	50.98	53.40	53.40	52.70	49.72
Jul 15	45.19	45.69	46.38	47.09	47.57	48.19	48.68	49.17	49.17	48.19	46.20	41.15
Jul 16	39.33	37.33	36.15	35.82	35.93	35.82	39.45	40.74	42.46	43.45	42.16	39.33
Jul 17	38.05	36.62	36.04	35.25	35.04	34.83	36.15	38.24	39.65	40.54	40.33	35.82
Jul 18	35.93	35.43	34.03	33.02	33.32	34.13	37.14	36.44	38.94	40.33	40.17	35.82
Jul 19	35.32	34.13	32.62	31.40	31.02	31.91	35.32	35.32	35.25	36.33	35.82	34.34
Jul 20	33.09	31.31	30.01	30.01	30.01	31.02	33.02	35.14	37.25	37.14	35.82	34.13
Jul 21	32.62	31.72	30.71	29.62	29.21	29.92	33.62	34.62	36.44	36.04	35.25	34.44
Jul 22	33.52	32.23	30.53	29.21	28.80	30.10	33.72	35.75	36.73	36.22	35.14	33.62
Jul 23	32.23	30.71	29.71	28.71	27.61	27.80	31.72	34.72	37.18	36.96	36.62	35.53
Jul 24	34.93	34.72	34.55	34.55	33.93	36.62	38.67	39.65	40.66	40.87	40.74	41.24
Jul 25	41.36	41.36	42.84	42.76	41.78	40.46	40.17	41.15	42.16	42.67	42.67	41.15
Jul 26	40.95	40.95	40.33	40.33	40.46	40.66	43.89	45.19	46.48	46.57	45.19	43.89

Table B-2. Cont.

Date	2400	0200	0400	0600	0800	1000	1200	1400	1600	1800	2000	2200
Date	265.20	29.03	35.50	43.41	53.08	64.90	79.35	97.03	118.64	145.07	177.38	216.89
Jul 27	42.46	43.19	41.95	41.65	41.44	41.86	45.69	47.90	48.68	49.17	48.68	48.48
Jul 28	48.87	47.18	51.09	50.98	52.70	49.42	48.29	47.57	50.52	49.42	45.87	46.67
Jul 29	43.98	40.46	40.66	38.67	37.56	36.44	38.67	43.19	44.07	42.97	40.05	37.44
Jul 30	35.82	34.34	32.62	32.33	32.43	32.53	33.62	35.43	37.56	38.05	35.43	34.34
Jul 31	33.32	32.53	31.91	29.50	28.40	27.89	30.53	33.42	37.93	37.14	36.51	34.34
Aug 1	31.53	30.10	29.41	28.92	28.31	29.12	32.23	34.93	37.03	37.93	38.55	38.86
Aug 2	39.45	40.54	38.67	37.56	37.03	37.33	37.56	39.45	41.15	38.43	36.15	33.22
Aug 3	31.62	30.62	29.62	28.92	28.20	28.20	30.53	35.68	37.25	38.05	37.03	34.62
Aug 4	32.92	31.53	30.22	29.71	30.01	32.10	36.73	35.82	38.67	38.67	37.86	38.67
Aug 5	39.85	38.55	39.97	41.15	41.65	42.24	43.58	45.46	45.87	46.38	45.46	46.38
Aug 6	46.06	45.05	44.38	41.57	40.17	36.73	37.74	36.77	41.65	41.15	38.43	36.22
Aug 7	33.42	32.01	31.31	30.71	30.22	30.10	32.10	37.14	39.33	36.84	37.25	34.34
Aug 8	32.92	31.62	30.22	29.12	28.31	27.89	28.51	31.12	35.53	36.15	34.62	31.53
Aug 9	29.92	28.71	27.61	26.90	26.31	25.89	26.90	29.62	33.83	34.13	33.52	32.53
Aug 10	30.32	30.22	30.32	29.50	30.01	31.12	31.91	32.10	35.82	36.04	35.43	34.24
Aug 11	32.92	32.72	33.62	34.93	33.62	32.33	33.42	36.04	36.51	37.93	37.25	35.04
Aug 12	33.22	32.33	30.10	28.80	27.89	27.11	29.62	33.72	35.82	36.22	36.15	34.24
Aug 13	32.53	31.21	29.92	28.60	27.80	27.00	30.10	34.13	36.04	36.96	36.22	35.32
Aug 14	34.13	33.42	32.33	31.53	30.81	29.15	32.10	35.68	36.96	37.33	37.33	36.44
Aug 15	35.53	34.93	38.55	37.44	36.84	35.43	36.62	35.75	37.44	37.93	37.25	36.62
Aug 16	36.22	34.62	33.52	32.92	37.03	36.96	34.44	35.14	36.51	39.33	37.14	37.56
Aug 17	36.62	36.44	36.04	35.14	34.83	35.25	36.51	37.44	38.24	37.74	37.56	36.22
Aug 18	35.43	34.62	33.62	32.33	31.40	31.53	33.93	36.96	38.63	39.14	39.33	38.94
Aug 19	38.36	36.84	36.33	36.44	35.43	35.14	35.53	35.82	39.65	40.17	39.97	38.24
Aug 20	36.22	35.14	34.93	33.42	32.92	34.03	36.15	38.55	40.05	41.15	41.95	41.15
AUG 21	40.99	40.17	39.85	38.43	36.33	36.62						

Table B-3. Calculated discharge for two-hourly intervals.

Date	Time											
	2400	0200	0400	0600	0800	1000	1200	1400	1600	1800	2000	2200
Jul 2							0.85	2.05	2.35	2.80	2.66	2.35
Jul 3	2.30	2.10	2.05	1.63	1.83	2.05	3.05	3.53	3.34	3.53	4.61	4.57
Jul 4	4.61	4.96	4.35	3.71	2.67	4.13	5.08	5.79	5.13	4.57	4.44	4.08
Jul 5	3.99	3.81	3.90	3.62	3.71	5.21	5.71	6.72	7.81	7.88	7.49	7.60
Jul 6	7.04	6.62	6.40	6.31	6.17	6.44	6.66	7.04	6.91	6.83	6.83	6.49
Jul 7	6.40	6.29	6.15	6.06	6.11	6.15	6.40	6.62	6.40	6.72	6.46	6.46
Jul 8	6.06	5.87	5.52	5.23	5.23	5.49	6.17	6.70	7.51	6.94	6.44	5.59
Jul 9	5.42	5.05	4.82	4.50	4.48	4.79	5.47	5.95	6.62	7.24	6.62	5.95
Jul 10	5.47	5.10	4.97	5.23	5.47	5.71	6.20	6.72	7.04	7.14	6.87	6.66
Jul 11	6.51	6.29	6.15	5.95	5.83	6.13	6.62	7.00	7.45	7.84	8.03	8.21
Jul 12	8.21	7.80	7.51	7.30	7.24	7.45	7.99	7.84	7.84	8.17	8.08	8.03
Jul 13	7.54	7.18	6.83	6.62	6.44	6.51	6.62	6.79	7.00	7.45	7.68	7.45
Jul 14	7.24	6.79	6.57	6.40	6.29	6.17	6.87	7.60	8.06	8.06	7.93	7.35
Jul 15	6.40	6.51	6.66	6.81	6.91	7.04	7.14	7.24	7.24	7.04	6.62	5.47
Jul 16	5.02	4.50	4.18	4.09	4.12	4.09	5.05	5.37	5.78	6.01	5.71	5.02
Jul 17	4.69	4.31	4.15	3.93	3.87	3.81	4.18	4.74	5.10	5.32	5.27	4.09
Jul 18	4.12	3.98	3.58	3.28	3.37	3.61	4.45	4.26	4.92	5.27	5.23	4.09
Jul 19	3.95	3.61	3.16	2.78	2.66	2.94	3.95	3.95	3.93	4.23	4.09	3.67
Jul 20	3.30	2.75	2.33	2.33	2.33	2.66	3.28	3.90	4.48	4.45	4.09	3.61
Jul 21	3.16	2.88	2.56	2.20	2.06	2.30	3.46	3.75	4.26	4.15	3.93	3.70
Jul 22	3.43	3.04	2.50	2.06	1.92	2.36	3.49	4.07	4.34	4.20	3.90	3.46
Jul 23	3.04	2.56	2.23	1.89	1.50	1.57	2.88	3.78	4.46	4.40	4.31	4.01
Jul 24	3.84	3.78	3.73	3.73	3.55	4.31	4.85	5.10	5.35	5.40	5.37	5.49
Jul 25	5.52	5.52	5.87	5.85	5.62	5.30	5.23	5.47	5.71	5.83	5.83	5.47
Jul 26	5.42	5.42	5.27	5.27	5.30	5.35	6.11	6.40	6.68	6.70	6.40	6.11

Table B-3. Cont.

Date	2400	0200	0400	0600	0800	1000	1200	1400	1600	1800	2000	2200
Jul 27	5.78	5.95	5.66	5.59	5.54	5.64	6.51	6.98	7.14	7.24	7.14	7.10
Jul 28	7.18	6.83	7.62	7.60	7.93	7.29	7.06	6.91	7.51	7.29	6.55	6.72
Jul 29	6.13	5.30	5.35	4.85	4.56	4.26	4.85	5.95	6.15	5.90	5.20	4.53
Jul 30	4.09	3.67	3.16	3.07	3.10	3.13	3.46	3.98	4.56	4.69	3.98	3.67
Jul 31	3.37	3.13	2.94	2.16	1.78	1.60	2.50	3.40	4.66	4.45	4.28	3.67
Aug 1	2.82	2.36	2.13	1.96	1.75	2.03	3.04	3.84	4.42	4.66	4.82	4.90
Aug 2	5.05	5.32	4.85	4.56	4.42	4.50	4.56	5.05	5.47	4.79	4.18	3.34
Aug 3	2.85	2.53	2.20	1.96	1.71	1.71	2.50	4.05	4.48	4.69	4.42	3.75
Aug 4	3.25	2.82	2.40	2.23	2.33	3.00	4.34	4.09	4.85	4.85	4.64	4.85
Aug 5	5.15	4.82	5.18	5.47	5.59	5.73	6.04	6.46	6.55	6.66	6.46	6.66
Aug 6	6.59	6.37	6.22	5.57	5.23	4.34	4.61	4.35	5.59	5.47	4.79	4.20
Aug 7	3.40	2.97	2.75	2.56	2.40	2.36	3.00	4.45	5.02	4.37	4.48	3.67
Aug 8	3.25	2.85	2.40	2.03	1.75	1.60	1.82	2.69	4.01	4.18	3.75	2.82
Aug 9	2.30	1.89	1.50	1.24	1.02	0.86	1.24	2.20	3.52	3.61	3.43	3.13
Aug 10	2.43	2.40	2.43	2.16	2.33	2.69	2.94	3.00	4.09	4.15	3.98	3.64
Aug 11	3.25	3.19	3.46	3.84	3.46	3.07	3.40	4.15	4.28	4.66	4.48	3.87
Aug 12	3.34	3.07	2.36	1.92	1.60	1.32	2.20	3.49	4.09	4.20	4.18	3.64
Aug 13	3.13	2.72	2.30	1.85	1.57	1.28	2.36	3.61	4.15	4.40	4.20	3.95
Aug 14	3.61	3.40	3.07	2.82	2.59	2.04	3.00	4.05	4.40	4.50	4.50	4.26
Aug 15	4.01	3.84	4.82	4.53	4.37	3.98	4.31	4.07	4.53	4.66	4.48	4.31
Aug 16	4.20	3.75	3.43	3.25	4.42	4.40	3.70	3.90	4.28	5.02	4.45	4.56
Aug 17	4.31	4.26	4.15	3.90	3.81	3.93	4.28	4.53	4.74	4.61	4.56	4.20
Aug 18	3.98	3.75	3.46	3.07	2.78	2.82	3.55	4.40	4.84	4.97	5.02	4.92
Aug 19	4.77	4.37	4.23	4.26	3.98	3.90	4.01	4.09	5.10	5.23	5.18	4.74
Aug 20	4.20	3.90	3.84	3.40	3.25	3.58	4.18	4.82	5.20	5.47	5.66	5.47
Aug 21	5.43	5.23	5.15	4.79	4.23	4.31	4.82	5.42	5.73	5.97	5.95	5.42
Aug 22	5.35	5.18	4.72	4.48	3.78	3.19						

1975). Standard error for the equation is 29.1. The regression curve has been plotted on a graph on which the x-axis is the log of the transmissivity measured in percent, and the y-axis is concentration measured in milligrams per litre.

Table B-4 shows the transmissivity readings and measured suspended sediment concentrations of 50 water samples from Sunwapta Lake, from which the regression equation was calculated.

3. Correlation and Scattergrams

Scattergrams were used to show the degree of correlation existing between discharge in the southeast stream and both dissolved and suspended sediment concentration in the southeast stream, at Pans B, 1, 2, 3, and 4, and in the outlet. The correlation coefficients for dissolved sediment concentration versus discharge were generally higher than those for suspended sediment concentration versus discharge. For suspended sediment concentration, the correlation coefficient increased with increased distance from the southeast stream. The equations for the 'best-fit' lines for each graph c an be written as

$$C_d = AQ + B \tag{B-5}$$

$$C_s = CQ + D \tag{B-6}$$

in which C_d is dissolved sediment concentration in milligrams per litre; C_s is suspended sediment concentration in milligrams per litre; A B, C, and D are constants,

Table B-4. Transmissivity readings and measured suspended sediment concentrations.

Sediment Concentration mg/l	Transmissivity Reading %
239.12	51.0
212.70	52.0
189.76	52.5
202.33	53.5
186.20	54.0
200.09	55.0
206.01	57.0
166.30	58.0
169.38	58.0
181.10	59.0
135.03	61.0
152.05	61.0
139.11	61.5
109.21	64.0
115.04	64.5
135.85	65.0
95.35	67.0
107.84	67.0
109.95	67.5
99.36	68.0
101.94	68.0
108.45	68.0
106.81	68.5
113.24	69.0
99.30	69.5
109.79	69.5
84.28	70.0
115.90	70.0
83.76	70.5
92.66	71.5
95.26	71.5
98.48	72.0
94.86	72.5
74.89	73.5
96.86	73.5
71.12	74.5
78.26	76.0
62.93	77.0
58.44	79.0
59.50	79.2
43.31	80.0
53.97	80.0
62.47	80.0
62.83	80.0
64.08	80.0

calculated using the Statistical Package for the Social Sciences (Nie et al., 1975); and Q is discharge in cubic metres per second.

Figures 20A to 20G in the text show the resulting 'best-fit' lines for each sampling site. The correlation coefficients for the regression lines in Figures 20A - 20G are shown in Table B-5.

Table B-5. Correlation coefficients for the regression lines in Figures 20A - 20G.

Site	Cs	Cd
stream	0.508	0.721
Pan B	0.701	0.619
Pan 1	0.570	0.529
Pan 2	0.727	0.543
Pan 3	0.684	0.504
Pan 4	0.698	0.355
Outlet	0.696	0.522

Appendix C

Particle-size Analysis of North Basin Sediment Pan Samples

Samples of material collected in north basin sediment pans throughout the field season were analysed in the physical laboratory of the Department of Geography, University of Alberta. Each sample was mechanically disaggregated with a mortar and pestle. A smaller sample, averaging 30g, was taken from each larger sample, chemically disaggregated using sodium hexametaphosphate (Calgon), and wet sieved to separate the coarser fraction from sediment less than 4 ϕ . Grain-size analysis of sediment less than 4 was carried out according to the standard hydrometer technique, except that a waterbath was not used, the temperature of the laboratory being relatively constant. The particle diameter is calculated from the formula:

$$D = k \sqrt{\frac{L}{T}} \qquad \text{(B-7)}$$

where D is particle diameter; k, a variable dependent on temperature and specific gravity (obtained from a table); L, a variable dependent on the hydrometer reading (obtained from a table); and T, elapsed time in minutes. The percentage of fine material remaining in suspension after each hydrometer reading was calculated, using the equation:

$$P = R \times \frac{Gs}{Gs-Gw} \times \frac{100}{W} \qquad \text{(B-8)}$$

where P is the percentage of fines remaining; G_s , the

specfic gravity of the sediment; R, the corrected hydrometer reading; G_w, the specific gravity of water (assumed 1.000); and W, the weight of soil dispersed (g/ml). The equation is based on that given in the American Society for Testing Materials (1964). Specfic gravity of the sediment was found, by analysis, to average 2.75.

Only 5 samples, from Pans 1, 1A and 3, were found to contain a significant (equal to or greater than 10 percent) proportion of material coarser than 4ϕ. The coarser fraction of each sample was dry sieved for 3 minutes by hand using sieve sizes 35, 80, 120, 170, and 230.

Figures C-1 - C-4 show the resulting particle-size distribution for samples from sediment pans 1 - 4. On each graph, the x-axis is particle size in ϕ scale values, and the y-axis is both percentage of material less than 4ϕ remaining in suspension after each hydrometer reading and percentage of material coarser than 4ϕ remaining on each sieve after dry sieving.

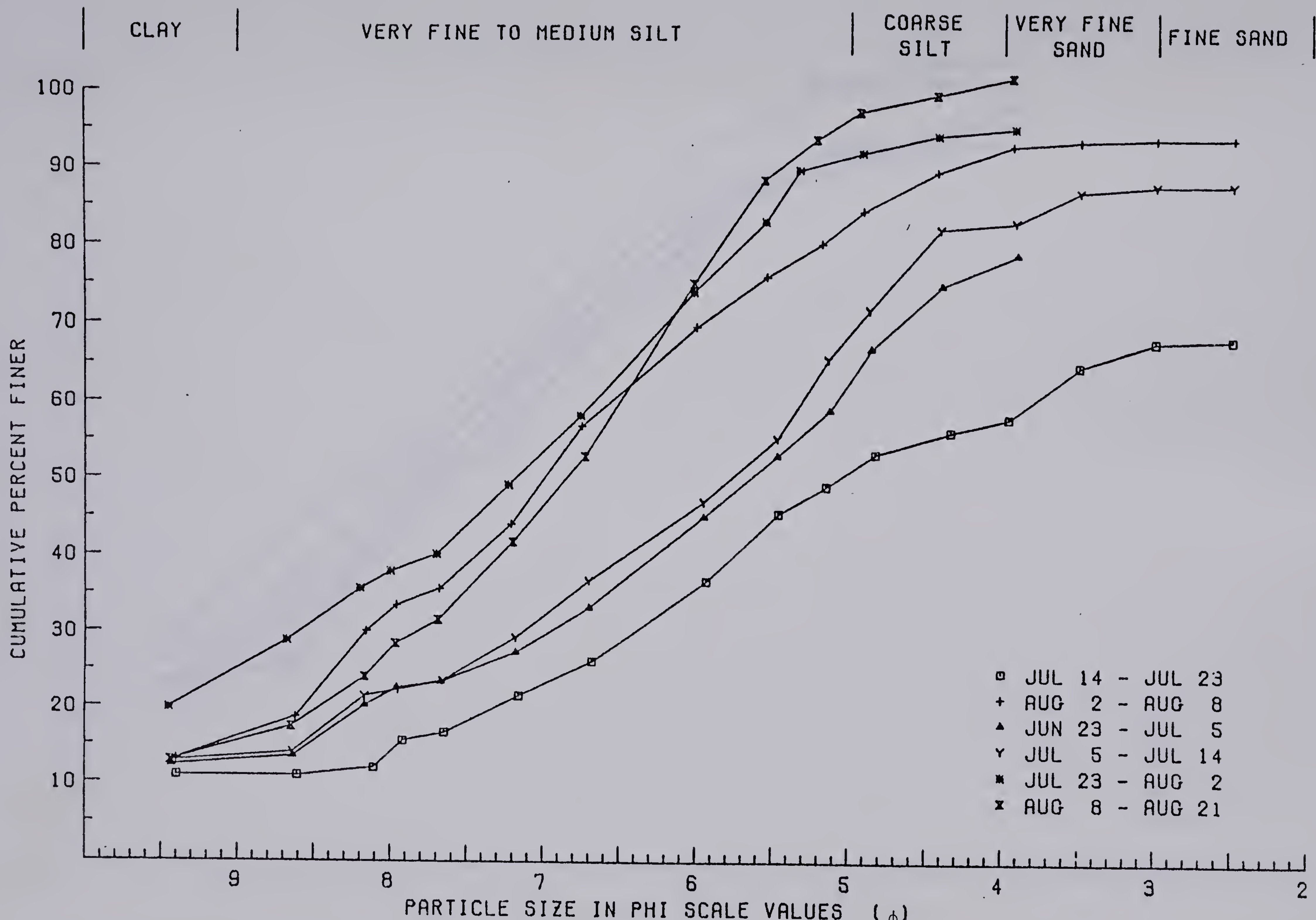

FIGURE C-1. PARTICLE SIZE DISTRIBUTION FOR PAN 1 SEDIMENT SAMPLES.

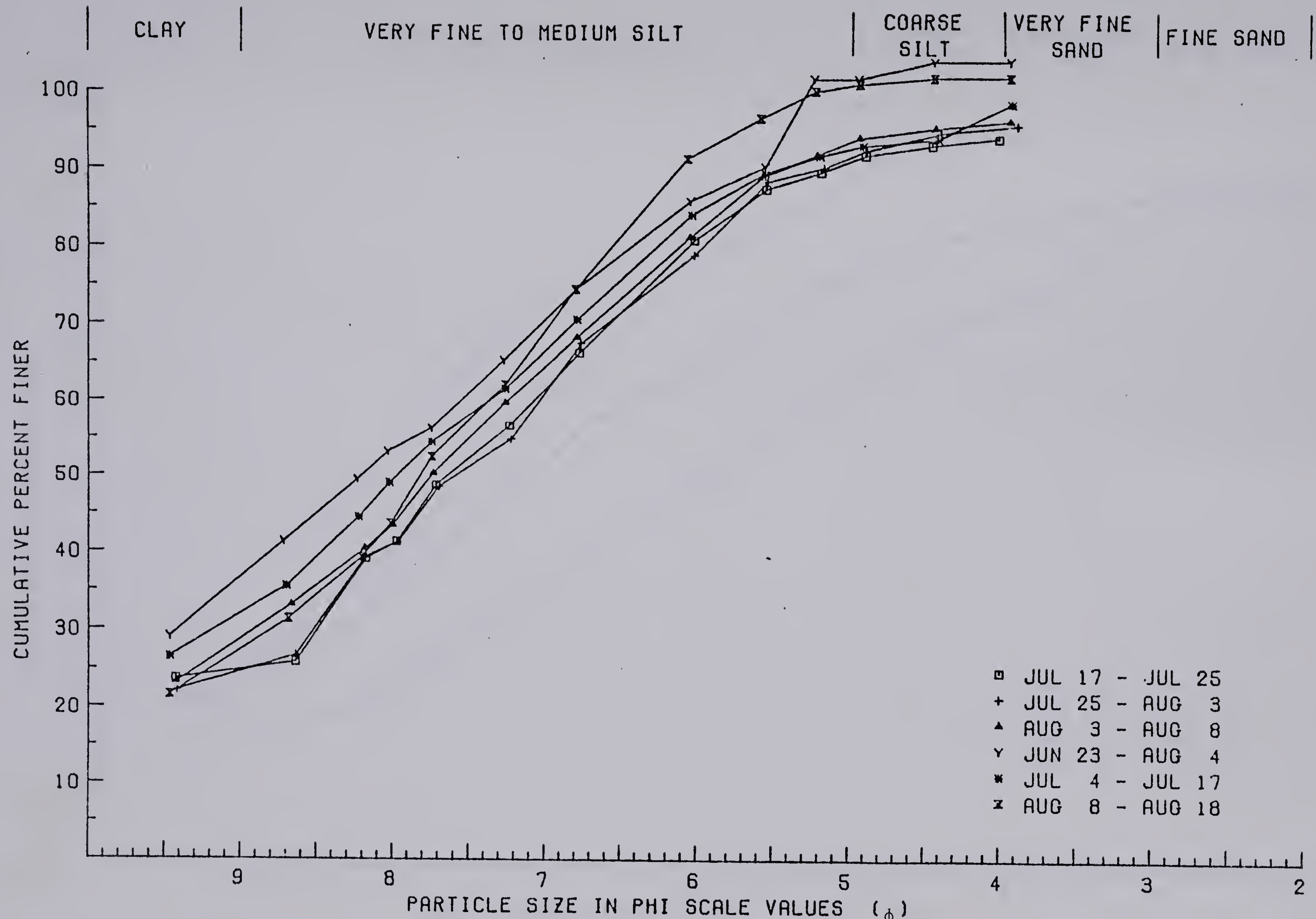

FIGURE C-2. PARTICLE SIZE DISTRIBUTION FOR PAN 2 SEDIMENT SAMPLES.

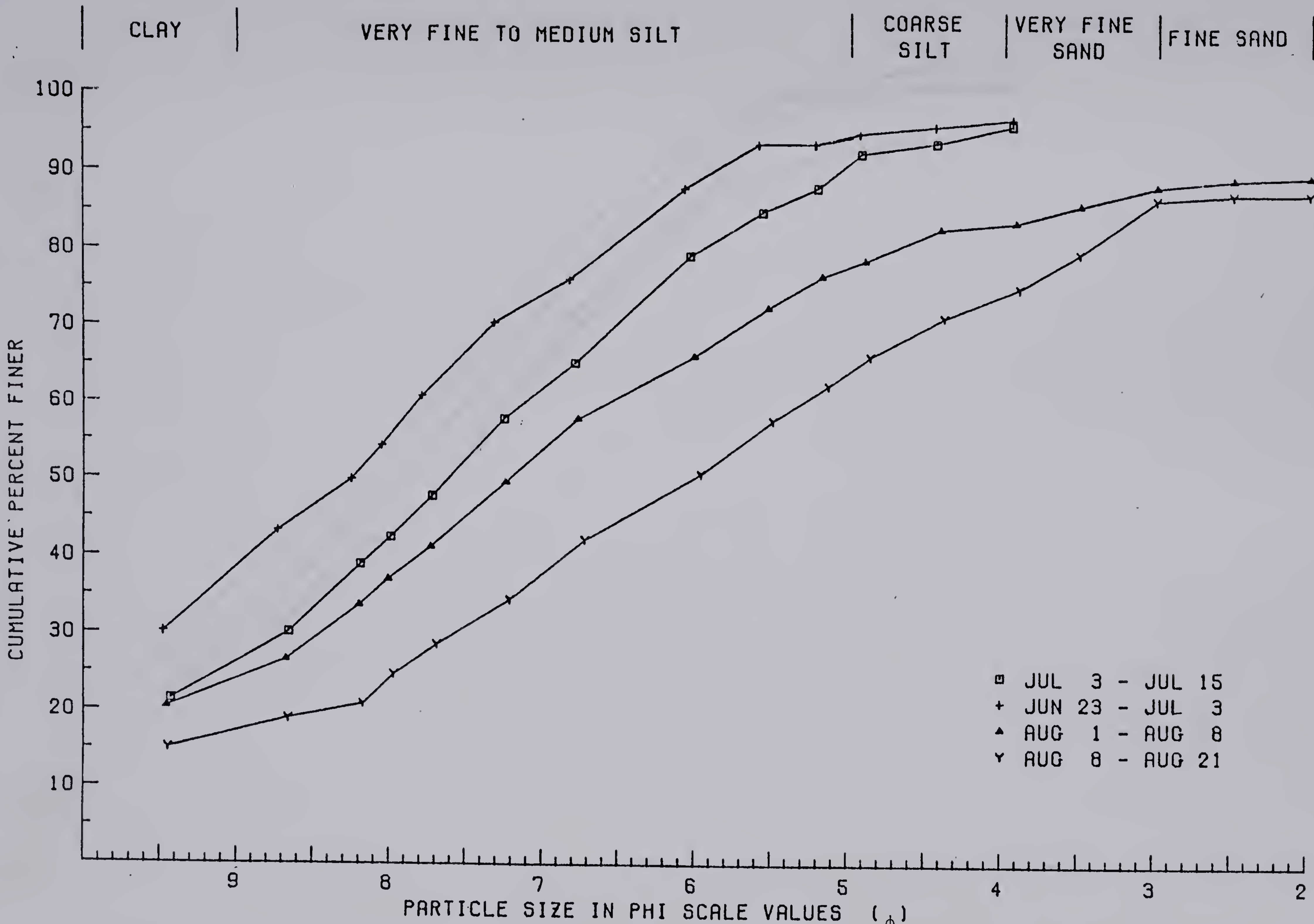

FIGURE C-3. PARTICLE SIZE DISTRIBUTION FOR PAN 3 SEDIMENT SAMPLES.

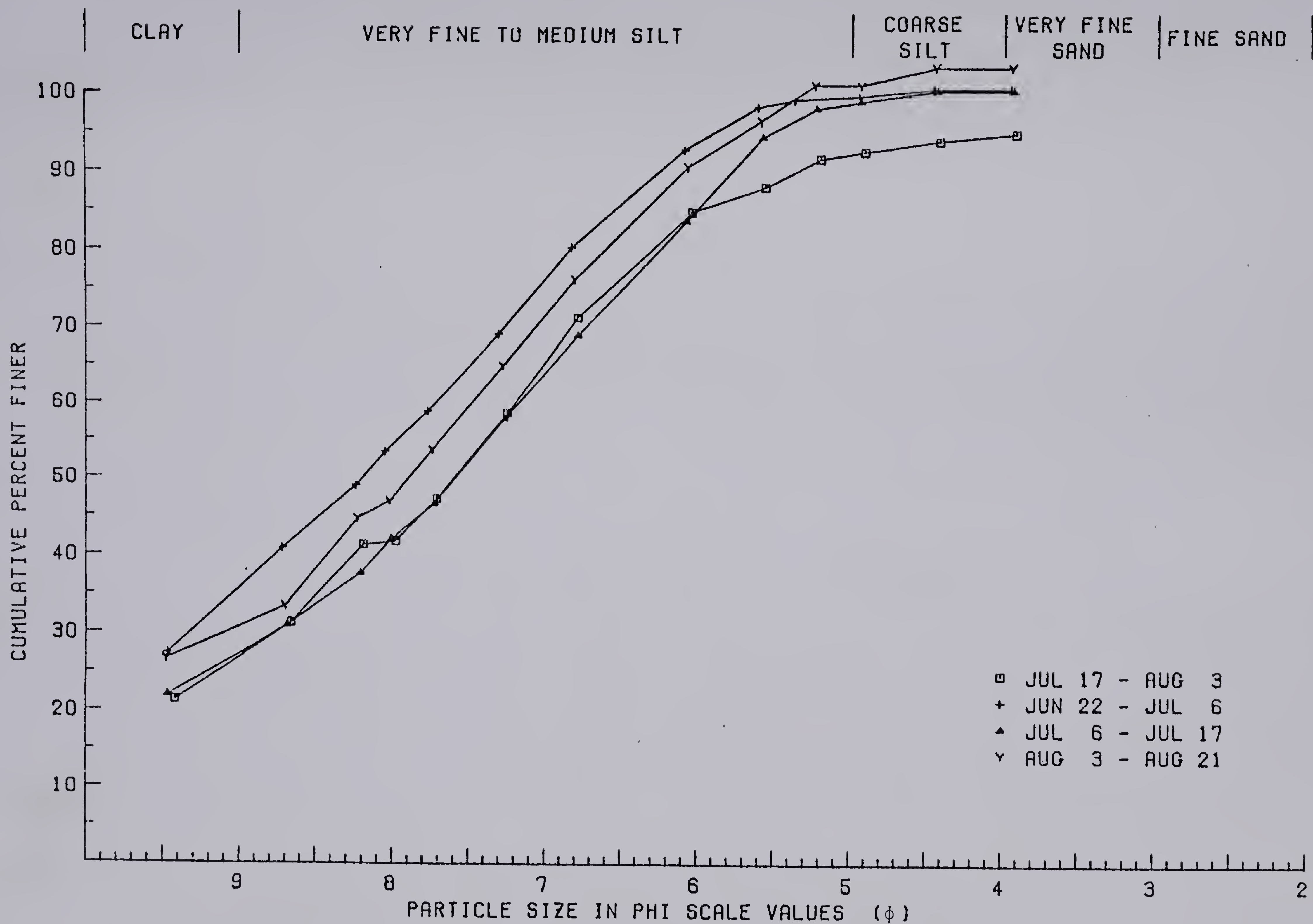

FIGURE C-4. PARTICLE SIZE DISTRIBUTION FOR PAN 4 SEDIMENT SAMPLES.

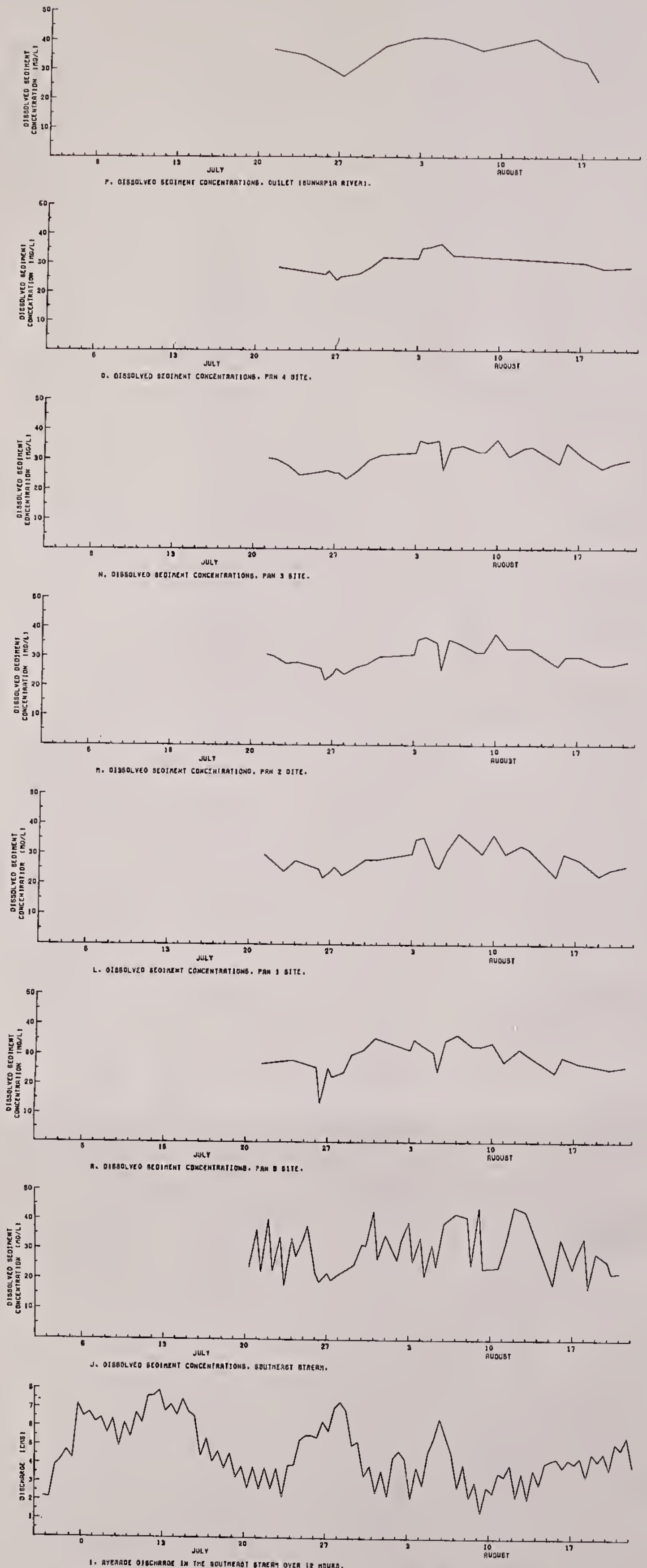

FIGURE 21 (CONT). SOUTHEAST STREAM DISCHARGE AND SEDIMENT CONCENTRATIONS IN THE SOUTHEAST STREAM AND IN SUNWAPTA LAKE.

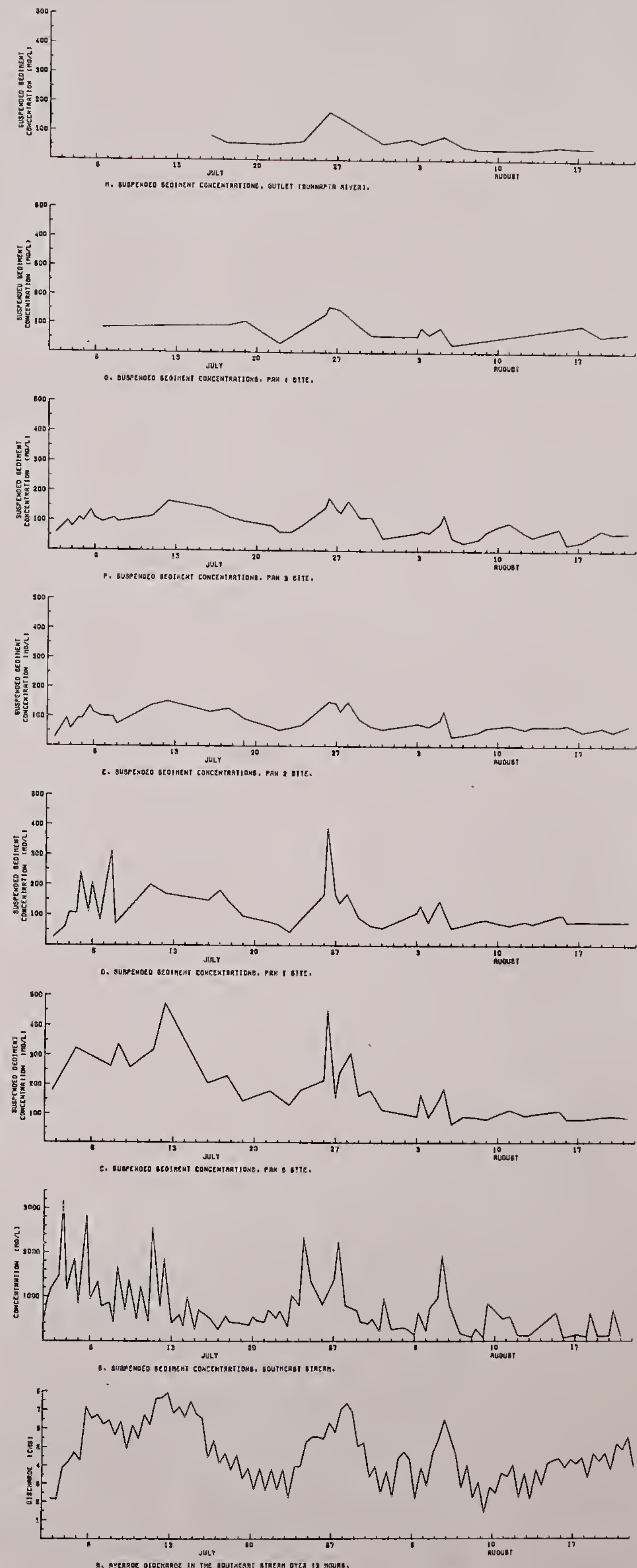

FIGURE 21. SOUTHEAST STREAM DISCHARGE AND SEDIMENT CONCENTRATIONS IN THE SOUTHEAST STREAM AND IN SUNWAPTA LAKE.